



DUDLEY KNOX LIBRARY  
NAVAL POSTGRADUATE SCHOOL  
MONTEREY CA 93943-5101





Approved for public release; distribution is unlimited.

Analysis of Drifting SOFAR Buoys  
in the Greenland Sea 1989-1990

by

David Hilton McCarren  
Lieutenant Commander, United States Navy  
B.S., Pennsylvania State University, 1979

Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY  
AND PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL  
December 1991

---

## REPORT DOCUMENTATION PAGE

|                                                                |  |                                                                                                   |                            |
|----------------------------------------------------------------|--|---------------------------------------------------------------------------------------------------|----------------------------|
| REPORT SECURITY CLASSIFICATION<br>Unclassified                 |  | 1b. RESTRICTIVE MARKINGS                                                                          |                            |
| SECURITY CLASSIFICATION AUTHORITY                              |  | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution is unlimited. |                            |
| DECLASSIFICATION/DOWNGRADING SCHEDULE                          |  | 5. MONITORING ORGANIZATION REPORT NUMBER(S)                                                       |                            |
| PERFORMING ORGANIZATION REPORT NUMBER(S)                       |  | 7a. NAME OF MONITORING ORGANIZATION<br>Naval Postgraduate School                                  |                            |
| NAME OF PERFORMING ORGANIZATION<br>Naval Postgraduate School   |  | 6b. OFFICE SYMBOL<br>(If Applicable)                                                              |                            |
| ADDRESS (city, state, and ZIP code)<br>Monterey, CA 93943-5000 |  | 7b. ADDRESS (city, state, and ZIP code)<br>Monterey, CA 93943-5000                                |                            |
| NAME OF FUNDING/SPONSORING ORGANIZATION                        |  | 6b. OFFICE SYMBOL<br>(If Applicable)                                                              |                            |
| ADDRESS (city, state, and ZIP code)                            |  | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER                                                   |                            |
|                                                                |  | 10. SOURCE OF FUNDING NUMBERS                                                                     |                            |
|                                                                |  | PROGRAM<br>ELEMENT NO.                                                                            | PROJECT<br>NO.             |
|                                                                |  | TASK<br>NO.                                                                                       | WORK UNIT<br>ACCESSION NO. |

TITLE (Include Security Classification)

ANALYSIS OF DRIFTING SOFAR BUOYS IN THE GREENLAND SEA 1989-1990

PERSONAL AUTHOR(S)

McCarren, David H.

TYPE OF REPORT

Master's Thesis

13b. TIME COVERED  
FROM TO

14. DATE OF REPORT (year, month, day)  
December 1991

15. PAGE COUNT  
84

SUPPLEMENTARY NOTATION

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

| COSATI CODES |       |          |
|--------------|-------|----------|
| FIELD        | GROUP | SUBGROUP |
|              |       |          |
|              |       |          |
|              |       |          |

18. SUBJECT TERMS (continue on reverse if necessary and identify by block number)

Greenland Sea, East Greenland Current, Jan Mayen Current, SOFAR floats, Fram Strait

ABSTRACT (Continue on reverse if necessary and identify by block number)

In an attempt to gain a better understanding of the intermediate depth circulation of the Greenland Sea, 16 SOFAR floats were launched into Fram Strait in 1988 and 1989. Between the fall of 1989 and the summer of 1990, five of these floats were tracked by autonomous listening stations (ALS) positioned to provide tracking in the southern portion of the Greenland Sea. One float (MZ86) provided tracking information for ten months of the ALS deployment period. The other floats provided tracking information ranging from several days to two months. These float tracks delineated the intermediate depth circulation around the Greenland Sea gyre. The MZ86 trajectory exited the Boreas Basin and crossed the Greenland Fracture Zone with a speed of approximately  $17 \text{ cm s}^{-1}$ . Along the Greenland continental slope the flow increased to  $28 \text{ cm s}^{-1}$  suggesting the presence of a bottom trapped boundary current. Near  $74^\circ\text{N}$  the trajectory turned eastward under the shallower warm core of the Jan Mayen Current at  $4 \text{ cm s}^{-1}$ . This leg closed the Greenland Sea gyre and also shows evidence of interactions with filaments of the Norwegian Atlantic Current (NAC) coming through the Mohns Ridge at these intermediate depths. Two other floats demonstrated tracks which crossed the Mohns Ridge and drifted farther to the east, mixing with the waters of the NAC.

DISTRIBUTION/AVAILABILITY OF ABSTRACT

UNCLASSIFIED/UNLIMITED

☐ SAME AS

☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION  
Unclassified

a. NAME OF RESPONSIBLE INDIVIDUAL  
R. H. Bourke

22b. TELEPHONE (Include Area Code)  
(408) 646-3270

22c. OFFICE SYMBOL  
OC/BF

# NAVAL POSTGRADUATE SCHOOL

## Monterey , California



# THESIS

Analysis of Drifting SOFAR Buoys  
in the Greenland Sea, 1989-1990

by

David H. McCarren

December 1991

Thesis Advisors:

J. C. Gascard  
R. H. Bourke

Approved for public release; distribution is unlimited.



## ABSTRACT

In an attempt to gain a better understanding of the intermediate depth circulation of the Greenland Sea, 16 SOFAR floats were launched into Fram Strait in 1988 and 1989. Between the fall of 1989 and the summer of 1990, five of these floats were tracked by autonomous listening stations (ALS) positioned to provide tracking in the southern portion of the Greenland Sea. One float (MZ86) provided tracking information for ten months of the ALS deployment period. The other floats provided tracking information ranging from several days to two months. These float tracks delineated the intermediate depth circulation around the Greenland Sea gyre. The MZ86 trajectory exited the Boreas Basin and crossed the Greenland Fracture Zone with a speed of approximately  $17 \text{ cm s}^{-1}$ . Along the Greenland continental slope the flow increased to  $28 \text{ cm s}^{-1}$  suggesting the presence of a bottom trapped boundary current. Near  $74^\circ\text{N}$  the trajectory turned eastward under the shallower warm core of the Jan Mayen Current at  $4 \text{ cm s}^{-1}$ . This leg closed the Greenland Sea gyre and also shows evidence of interactions with filaments of the Norwegian Atlantic Current (NAC) coming through the Mohns Ridge at these intermediate depths. Two other floats demonstrated tracks which crossed the Mohns Ridge and drifted farther to the east, mixing with the waters of the NAC.

120313  
M16468  
c.1

TABLE OF CONTENTS

I. INTRODUCTION.....1

    A. OVERVIEW.....1

    B. BACKGROUND.....3

    C. SOFAR FLOATS .....8

    D. ARCTEMIZ.....10

    E. PURPOSE .....11

II. DATA .....12

    A. DATA PROCESSING .....17

    B. PROGRAM ERRORS .....23

III. RESULTS.....29

    A. MZ86 .....29

    B. AR50.....41

    C. AR57.....43

    D. AR48.....43

    E. MZ83.....46

    F. DISCUSSION.....46

IV. CONCLUSIONS.....55

LIST OF REFERENCES.....57

APPENDIX A .....59

APPENDIX B.....65

APPENDIX C.....68

APPENDIX D.....70

APPENDIX E.....72

INITIAL DISTRIBUTION LIST .....74

## LIST OF TABLES

|                                                                                   |    |
|-----------------------------------------------------------------------------------|----|
| Table 1. Details of 1988 Float and ALS Deployments .....                          | 13 |
| Table 2. Details of 1989 Float and ALS Deployments.....                           | 17 |
| Table 3. Program Functions and Files.....                                         | 20 |
| Table 4. Duration of Floats Tracked During 1989 by the Southern ALS<br>Array..... | 29 |
| Table 5. Details of the Individual MZ86 Tracking Legs.....                        | 30 |

## LIST OF FIGURES

|                                                                                                                                                                                                                                   |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1. A schematic chart showing the components of the Greenland Sea and Fram Strait bathymetry. ....                                                                                                                          | 4  |
| Figure 2. A chart showing the circulation in the Greenland Sea and Fram Strait ( modified from <i>Koltermann and Lüthje</i> , 1989). ....                                                                                         | 5  |
| Figure 3. Circulation of the WSC showing both the coastal eastern branch of the WSC and an inferred branch following the seaward contours of the Yermak Plateau. ....                                                             | 7  |
| Figure 4. 1988 ALS (solid dots) and float deployment locations. ....                                                                                                                                                              | 14 |
| Figure 5. 1988 Trajectories of Floats AR48, AR50, and AR57. ....                                                                                                                                                                  | 15 |
| Figure 6. 1989 ALS and float deployment locations. ....                                                                                                                                                                           | 16 |
| Figure 7. Waterfall display of the ALS raw data, signal versus time. ....                                                                                                                                                         | 18 |
| Figure 8. Bar chart showing time periods each float was tracked during the 1989 ALS deployment. ....                                                                                                                              | 19 |
| Figure 9. Processing flow chart. ....                                                                                                                                                                                             | 21 |
| Figure 10. Results of cubic spline smoothing. ....                                                                                                                                                                                | 24 |
| Figure 11. Plot of float MZ86 with the improperly applied ALS 17 clock drift. ....                                                                                                                                                | 25 |
| Figure 12. Plot of float MZ86 with the ALS 17 clock drift applied correctly. ....                                                                                                                                                 | 28 |
| Figure 13. Trajectory of Float MZ86. ....                                                                                                                                                                                         | 31 |
| Figure 14. Two SOFAR float drift tracks during MIZEX 84. ....                                                                                                                                                                     | 32 |
| Figure 15. Velocity series for MZ86 from 27 September 1989 to 3 August 1990. ....                                                                                                                                                 | 33 |
| Figure 16. Trajectory of satellite tracked buoys (drogue at 30 m) from MIZEX '87 (from <i>GSP Group</i> , 1989). ....                                                                                                             | 35 |
| Figure 17. Vertical baroclinic current velocity section at 77.5°N. ....                                                                                                                                                           | 36 |
| Figure 18. Section across the continental slope in the Arctic Basin showing an intensified boundary current trapped along the continental slope with the velocity increasing toward the bottom (from <i>Aagaard</i> , 1989). .... | 38 |
| Figure 19. Vertical density ( $\sigma_t$ ) cross section across the Denmark Strait (from <i>Smith</i> , 1976). ....                                                                                                               | 39 |
| Figure 20. Cross section at 79°N showing the southward flowing bottom boundary current forced against the continental slope (from <i>Koltermann and Lüthje</i> , 1989). ....                                                      | 40 |

Figure 21. 1988 and 1989 trajectories of Float AR50.....42

Figure 22. 1988 and 1989 trajectories of Float AR57. ....44

Figure 23. 1988 and 1989 trajectories of Float AR48. ....45

Figure 24. Launch position and tracked positions of Float MZ83.....47

Figure 25 Plot of tracks of MZ86, AR50, and AR57 on detailed bathymetry  
of the Greenland Sea.....49

Figure 26. Detailed track of MZ86 leg 3, showing broad meanders as the  
float tracked to the northeast. ....50

Figure 27. Current velocity at the 341 m level of the essentially barotropic  
and wind-forced model of *Legutke* (1990). ....52

Figure 28. Energy density spectrum of the MZ86 velocity series from 3 July  
1990 to 4 August 1990.....54

## ACKNOWLEDGEMENTS

As with any project of this nature there are many individuals who contribute to its successful completion. Two of particular note are Catherine Rouault of LODYC and Pedro Tsai of the Navy Postgraduate School. Catherine spent much effort in deciphering and answering my many FAX messages as she helped me debug the software by long distance. Pedro offered his assistance in training a UNIX novice into a true UNIX amateur and helped recompile several programs involved in the processing.

A special thanks to my co-advisors, Professors Bourke and Gascard. Professor Gascard made the data and software available to me for this project and provided guidance and careful tutelage from ~3000 miles (~5500 km) away. And Professor Bourke, being my advisor in residence, had the daily task of talking me through problems and most importantly keeping me focused and on track.

To these and my family and friends who helped me through this, thank you.

# I. INTRODUCTION

## A. OVERVIEW

Fram Strait, the narrow body of water between the east coast of Greenland and the Svalbard Archipelago, has long been recognized as the most important link between the cold polar waters of the Arctic Ocean and the warmer and saltier oceans to the south. On the east side of the strait warm, saline Atlantic Water at the surface is carried northward into Fram Strait and enters the Arctic Basin by flowing under the cold surface waters. To the west, southward flowing currents carry the cold Arctic surface waters and large volumes of ice southward along the eastern coast of Greenland. This results in very large transports of heat, salt, and momentum through Fram Strait. In addition, this exchange contributes to ventilation of the mid-depth and deeper waters of both the Arctic Ocean and the Greenland Sea.

The Greenland Sea is an area where deep convective processes have been observed and is considered to be a major producer of the deep waters found in the more southerly oceans. The overall circulation controls the rate of convection by varying the sensible heat and fresh water to the central gyre. These currents also redistribute the ventilated waters and the other mixing products. Because of its role in ventilating the deep oceans, the Greenland Sea plays an important role in the world climate system by controlling a large part of the global thermohaline circulation. An understanding of the large-scale three dimensional circulation in the Greenland Sea is important to the understanding of the global impact of

changes in the ventilation of the deep water and the thermohaline circulation. (Rudels *et al.*, 1989, *GSP Group*, 1990)

The mean large-scale surface currents of the Greenland Sea are reasonably well understood. Many studies using satellite-tracked floating buoys, satellite ice drift observations and dynamic height calculations have contributed to this knowledge (Bourke *et al.*; 1987, Johannessen *et al.*; 1987, Quadfasel *et al.*; 1987, Bourke *et al.*, 1991 ). Circulation of the deep currents is not as well understood. Limited knowledge has been gained from some deep current meter moorings (Muench *et al.*, 1986; Foldvik *et al.*, 1988; Aagaard *et al.*, 1991) and some studies with deep drifting buoys (Gascard *et al.*, 1988). These have been limited to the vicinity of Fram Strait and the East Greenland Shelf. Part of the mission of the Greenland Sea Project (GSP) was to gain additional knowledge of the deep currents of the basin (*GSP Group*, 1990). To this end, twelve subsurface floats and four tracking stations were deployed in September 1988 in the vicinity of Fram Strait. Four more floats were launched in April and May 1989 in dynamic features (eddies) in Fram Strait. In August 1989 three additional tracking stations were deployed farther south in the Greenland Sea in order to continue tracking these previously launched floats.

This study examines the trajectories of several of the aforementioned, acoustically-tracked, drifting SOFAR floats as they transitted through the Greenland Sea and around the Greenland Sea Gyre. These floats transmit acoustic signals at scheduled intervals that are received by the stationary tracking stations. The tracking stations record the time the signal was received. A combination of two or more of these received signals are used to determine the float position (Manley *et al.*, 1989). Decoding the data retrieved from the

tracking stations deployed in 1989 and analysis of the float trajectories is the focus of this thesis.

## B. BACKGROUND

The Greenland Sea is a semi-enclosed basin delineated to the north by Fram Strait, to the west by the Greenland coast, to the south by the Jan Mayen Fracture Zone, and to the east by Mohns-Knipovich Ridge System. Figure 1 is presented as an overview of the geography of the Greenland Sea. This sea can be further divided into two basins, the Boreas Basin to the north and the Greenland Basin to the south. The two basins are separated by the Greenland Fracture Zone. Both basins have depths in excess of 3000 m. The east Greenland continental shelf makes up a significant portion of the Greenland Sea, extending to the east for over 350 km at depths less than 400 m (*Muench et al.*, 1986). The circulation of the Greenland Sea is dominated by the cyclonic circulation of the Greenland Sea Gyre, which is driven by the wind stress curl (*Johannessen et al.*, 1987).

The West Spitsbergen Current (WSC) carries warm, saline Atlantic Water (AtW) northward on the eastern side of the Greenland Sea (Figure 2). The cold, fresh East Greenland Current (EGC) flows southward on the western side. At the northern margin, in Fram Strait, a portion of the WSC dives beneath the Polar Water (PW) north of Svalbard into the Eurasian Basin. Between 78°N and 81°N a branch of the WSC turns westward across Fram Strait (*Bourke et al.*, 1988) and then turns southward converging with the EGC at the continental shelf break. This flow continues southward as the Return Atlantic Current (RAC) with its

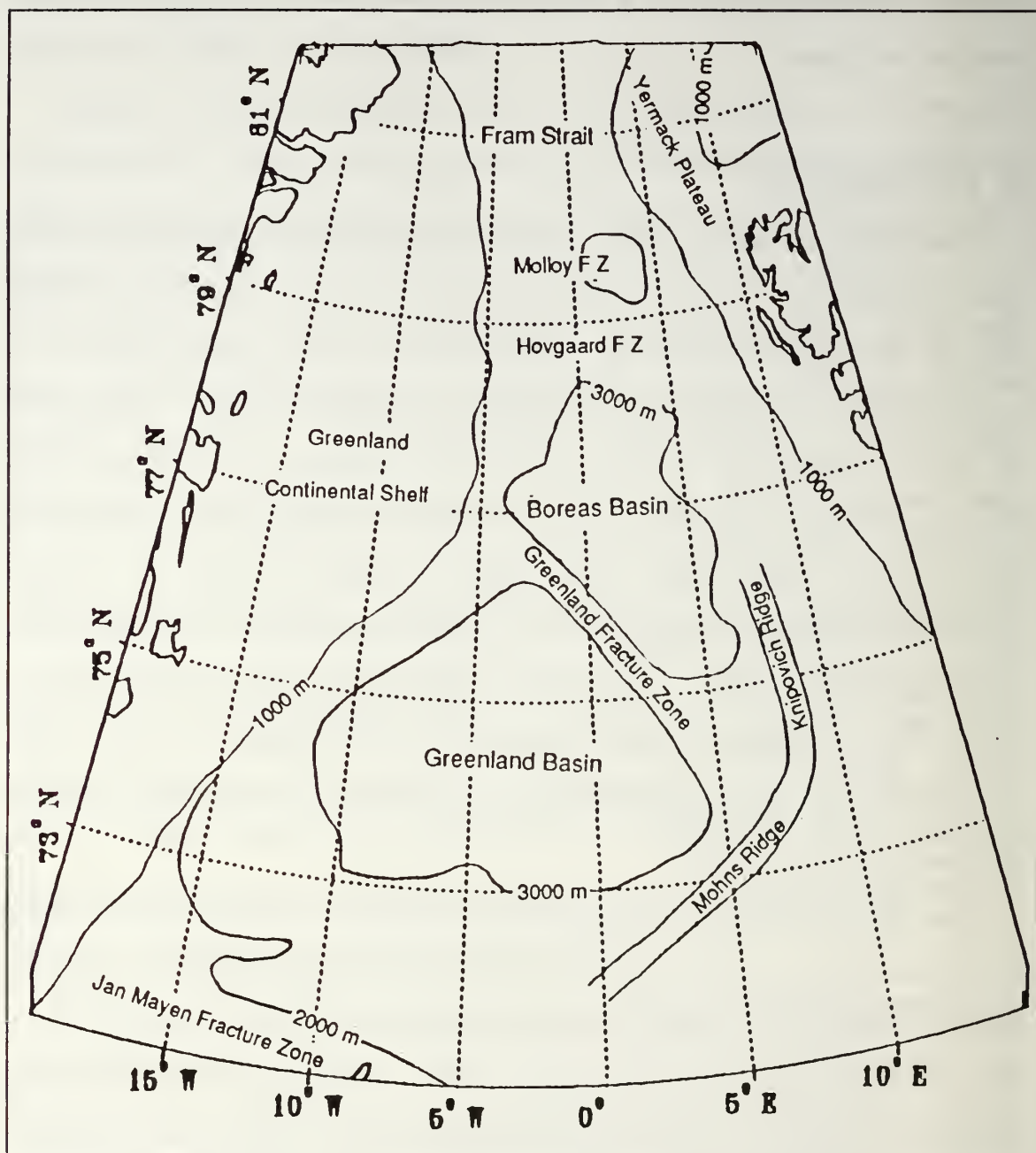


Figure 1. A schematic chart showing the components of the Greenland Sea and Fram Strait bathymetry. The 2000 m isobath is used to delineate the rise of the Jan Mayen Fracture Zone and becomes nearly coincident with the 1000 m contour along the Greenland continental slope. The 3000 m isobath is used to define the center of both the Boreas and Greenland Basins, a generalization of the 2000 m isobath was used to delineate Mohs Ridge.

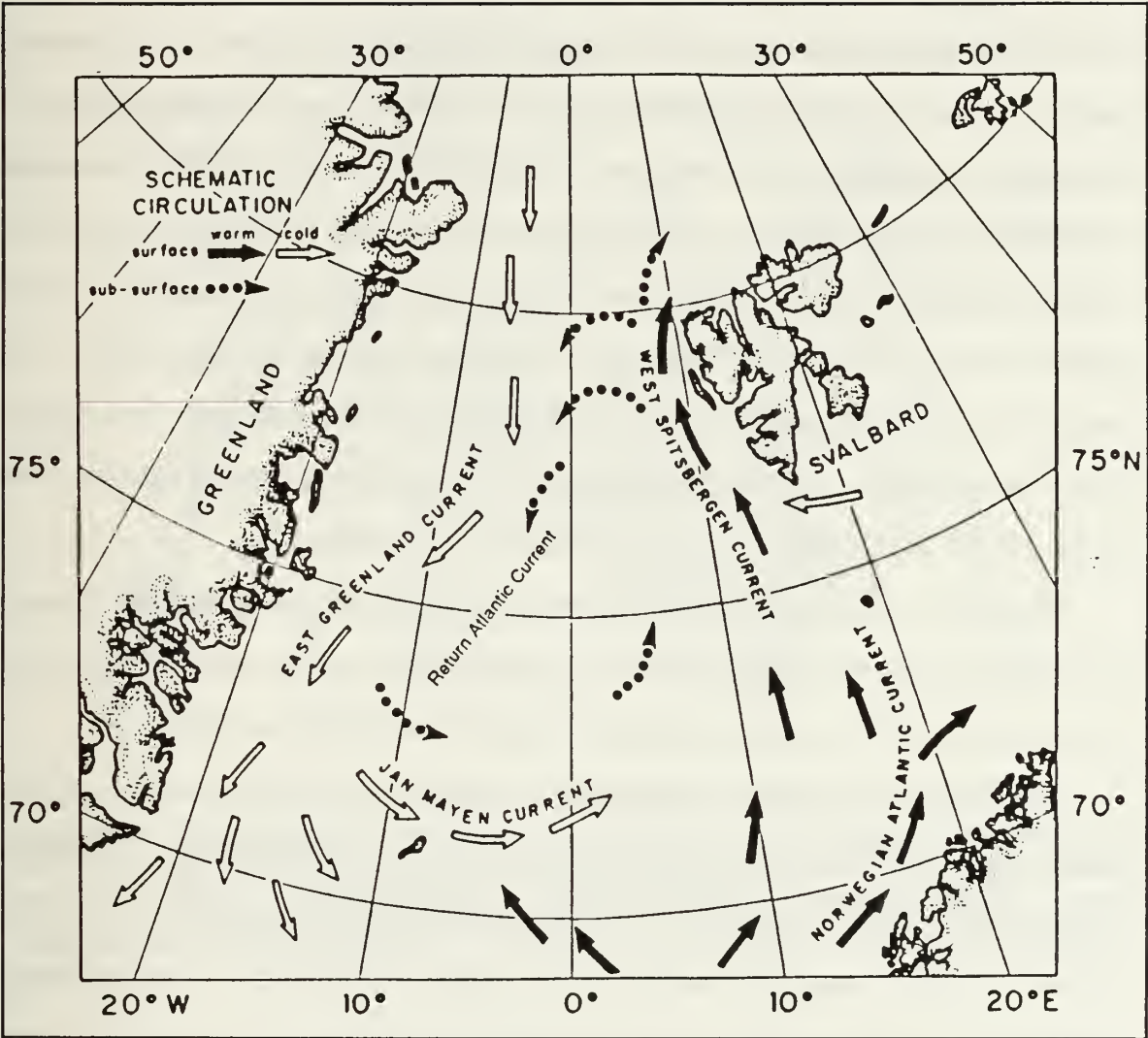


Figure 2. A chart showing the circulation in the Greenland Sea and Fram Strait ( modified from Koltermann and Lüthje, 1989).

core beneath and seaward of the PW of the EGC. The RAC is separated from the PW of the EGC by the East Greenland Polar Front (EGPF). At the southern edge of the Greenland Sea the Jan Mayen Current (JMC) turns to the east, north of the Jan Mayen Fracture Zone (JMFZ) to close the Greenland Sea Gyre.

The EGC is a broad southward flow originating in the northern reaches of Fram Strait and extending laterally from the Greenland coast to the continental slope. It can be vertically partitioned into two distinct components. The first is the broad, predominantly barotropic, southern flow overlying the Greenland continental shelf and slope. The second part of the EGC is a shallow (~100-200 m) baroclinic near-surface layer. Part of this surface layer is a narrow (~50 km) baroclinically driven jet that generally follows the continental shelf break. The core of the jet is coincident with the EGPF which separates the cold, low salinity water being carried from the Arctic Basin from the warmer, higher salinity water of the central RAC. (*Paquette et al.*, 1985; *Hopkins*, 1988)

The WSC is the northernmost extension of the Gulf Stream Current System. The WSC is driven by the topographic funneling effect of the cyclonic circulation in the Greenland Sea against the Svalbard shelf break (*Morison*, 1991).

The EGC and the WSC come together in Fram Strait. The interaction of these nearly opposing flows causes complex features to develop in the strait. The WSC begins to dive beneath the EGC as it approaches the EGPF near 80°N. The WSC breaks into two separate branches as it enters Fram Strait. The first turns eastward across the continental shelf north of Svalbard. The second turns westward as two flows, a southern limb across the Hovgaard Fracture Zone and a northern limb in the Molloy Fracture Zone and central Fram Strait but limited to



the area south of  $81^{\circ}\text{N}$ . Figure 3 shows the characteristic flow in Fram Strait. The westerly branch becomes the Return Atlantic Current (RAC) after crossing the strait and then turning southward along the continental shelf break. (*Bourke et al.*, 1987)

The Jan Mayen Current (JMC) appears at the surface as both a branch of the EGC projecting eastward as the southern limb of the Greenland Gyre and as a meander to the EGC flow (Figure 2) (*Blythe*, 1990). The barotropic flow of the intermediate and deep water continues to the east roughly following the topography of the JMFZ. The JMC is characterized by a near surface tongue of cold and fresh Polar Water (PW) projecting eastward around  $73^{\circ}\text{N}$ . It may also be discerned by the eastward turning of the warm, saline intermediate waters of the RAC at  $\sim 100\text{ m}$  depth. This water, termed the Jan Mayen Atlantic Intermediate Water (JMA<sub>AtIW</sub>) by *Hopkins* (1988), is displaced about 75 km north of the PW tongue and can be traced eastward across Mohns Ridge until its ultimate merger with the intermediate water of the Norwegian Atlantic Current (NAC) (*Bourke et al.*, 1991).

### C. SOFAR FLOATS

Acoustically-tracked Lagrangian drifting floats have been used with great success in observing the deep currents in the mid-latitudes (*Owens*, 1984). Because of its exploitation of the Deep Sound Channel (DSC), this technology has taken on the name SOFAR from Sound Fixing And Ranging and refers to floats which transmit an acoustic signal to a moored receiver. SOFAR floats were originally designed to exploit the long range propagation paths of the DSC; in the Arctic regions this path is not available.

The propagation characteristics in these northern latitude waters are upward refracting at all depths due to the overall positive sound speed gradient found in Arctic waters. This situation is often termed half channel propagation. For long range propagation the half channel path is dependent on multiple surface interactions. Therefore the characteristics of the surface at the reflection nodes are important. Various conditions of under-ice-roughness and surface roughness of the open ocean waters affect the detection ranges of the drifting floats, especially at higher frequencies. Hence the ranges expected using SOFAR floats in the Arctic are not as great as those expected in mid-latitude waters. For floats using 260 Hz acoustic projectors, ranges in the mid-latitudes of 1000-2000 km are not uncommon; expected ranges in the central Arctic are 150 - 350 km (*Manley et al.*, 1989).

SOFAR floats, made of aluminum cylinders or glass spheres which are less compressible than sea water, can be set to drift at a constant depth. A careful pre-launch ballasting procedure is used to define the level at which the float will drift. These floats can be set to signal at predetermined intervals, in this case three times a day at eight hour intervals. (*Manley et al.*, 1989)

Two different listening devices are used to record the arrival time of the float signals. One of these, the autonomous listening station (ALS), receives the acoustic signals and records them on tape. The signals are processed after the ALS has been recovered at the end of the deployment period (*Manley et al.*, 1989). A second device is the Arctic Relay Station (ARS) which receives and records the float signals on board a deep moored instrument and then transmits the signals up a mooring cable to a surface float moored above it. The surface

float then transmits the data to a shore station via the ARGOS data relay system. (Manley *et al.*, 1989)

In both cases post processing analysis is necessary to extract the time of arrival (TOA) data for a particular float as received by two or more listening stations. The floats are programmed to transmit their acoustic signals on a predetermined schedule; hence by comparing the TOA's from different stations, spherical geometry techniques can be used to locate the float (Manley *et al.*, 1989). This technique is similar to electronic navigation methods such as those used in LORAN. The in-situ trajectories are plotted from the individual float positions.

#### D. ARCTEMIZ

The ARCTEMIZ program, sponsored by the Centre National de la Recherche Scientifique and the Institut Francais de Recherche pour l'Exporation de le Mer (IFREMER), and also a component of the Greenland Sea Project, involved a substantial effort to launch and monitor SOFAR floats in and around Fram Strait (Manley *et al.*, 1989). Twelve SOFAR floats were launched in Fram Strait during the summer of 1988. Eight of these floats were employed to investigate the flow of the intermediate depth Atlantic Water and so were set for medium depths of 300 to 400 m. Four were set to depths of 1000 to 1100 m to examine the behavior of the Deep Water. To monitor the trajectories of these twelve floats three ALSs were deployed in northern Fram Strait. This northern ALS array was retrieved one year later in the summer of 1989. Three additional ALSs were deployed farther to the south in the Greenland Basin in September 1989. It was anticipated that the floats launched in the previous year could be redetected and

tracked through the Greenland Sea and around the gyre. Four additional floats were also launched in the spring of 1989 into eddy-like features in Fram Strait. The southern ALSs were retrieved in August 1990.

Plots of the raw data from the southern ALS array showed the arrival of acoustic signals from three floats launched in Fram Strait in 1988. Two of the four floats deployed in 1989 were also tracked. One of these was tracked over a 10 month period.

## **E. PURPOSE**

The purpose of this study is to examine the data acquired by the three ALSs deployed in the Greenland Sea from September 1989 to August 1990. Adequate data records were available for five floats to be studied. The trajectories derived from the acoustically-tracked floats are analyzed with regard to their mean and eddy motion, and the relationship to known fronts, currents and bathymetric features.

## II. DATA

The SOFAR float data consist of the recorded time of arrivals (TOA) of the float signals as received at an ALS. By using the TOA from three ALSs for a given float, the instantaneous float position and the drift of the float's internal clock can be estimated using simple spherical geometry and a nonlinear least squares fit (*Manley et al.*, 1989). Processing software from the Laboratoire D'Océanographie Dynamiques et de Climatologie (LODYC), Paris, has been modified for use in this study and is described below.

As part of the ARCTEMIZ project, twelve SOFAR floats and three ALSs were deployed in Fram Strait in August - September 1988 west of Spitsbergen. The intent was to examine the circulation of the intermediate and deep waters in Fram Strait. The initial launch position of each float and the mooring positions of the 1988 ALSs are illustrated in Figure 4. Table 1 provides the details of these deployments.

The ALSs were recovered in 1989 and the data processed by Laboratoire D'Océanographie Dynamique et de Climatologie (*Gascard*, 1990). Three of the 1988 floats (AR48, AR50, and AR57) were still trackable a year later by the 1989 ALSs. As an aid to their later analysis, their trajectories during 1988 are shown in Figure 5.

In 1989 three ALSs were deployed in an attempt to regain contact with the floats launched in 1988. The mooring locations for these ALSs were designed to allow adequate tracking of the presupposed float drift paths and to ensure reasonable mooring depths. One ALS was moored on the shallow rise of the Greenland Fracture Zone and two on shallow depth spurs of the Jan Mayen

Fracture Zone. Four additional intermediate depth (200 m) floats were launched into eddy-like features in Fram Strait during April and May 1989. One float MZ86 was specially ballasted to initially settle at 200 m then settle at 1 m per day until reaching 500 m and then remaining at that depth. The 1989 deployment locations of the ALSs and floats are shown in Table 2 and Figure 6. Only the float trajectories tracked by the 1989 ALSs are analyzed in this study.

**TABLE 1. DETAILS OF 1988 FLOAT AND ALS DEPLOYMENTS**

| Float # | Depth  | LAT      | LON      | Launch  |
|---------|--------|----------|----------|---------|
| 46      | 1000 m | 79 27.8N | 5 29.7E  | 8/29/88 |
| 47      | 1000 m | 78 00.3N | 2 51.2E  | 9/6/88  |
| 48      | 1065 m | 78 45.2N | 4 56.7E  | 9/4/88  |
| 49      | 1055 m | 78 44.7N | 1 27.8E  | 9/5/88  |
| 50      | 340 m  | 77 15.0N | 10 29.0E | 9/6/88  |
| 51      | 300 m  | 78 01.8N | 8 45.7E  | 8/22/88 |
| 52      | 340 m  | 79 30.7N | 8 05.3E  | 9/3/88  |
| 53      | 315 m  | 79 29.0N | 6 32.6E  | 8/29/88 |
| 54      | 320 m  | 79 00.0N | 6 29.0E  | 8/29/88 |
| 55      | 330 m  | 79 00.4N | 7 24.1E  | 8/28/88 |
| 56      | 345 m  | 76 44.9N | 12 00.9E | 9/7/88  |
| 57      | 335 m  | 78 29.2N | 8 19.5E  | 8/21/88 |

| ALS # | Depth | LAT      | LON      | Launch  | Recover |
|-------|-------|----------|----------|---------|---------|
| 7     | 900 m | 75 05.0N | 1 49.6E  | 8/16/88 | 8/19/89 |
| 11    | 714 m | 80 06.4N | 4 34.9E  | 8/30/88 | 9/2/89  |
| 18    | 817 m | 80 48.3N | 12 56.3E | 8/31/88 | 9/3/89  |

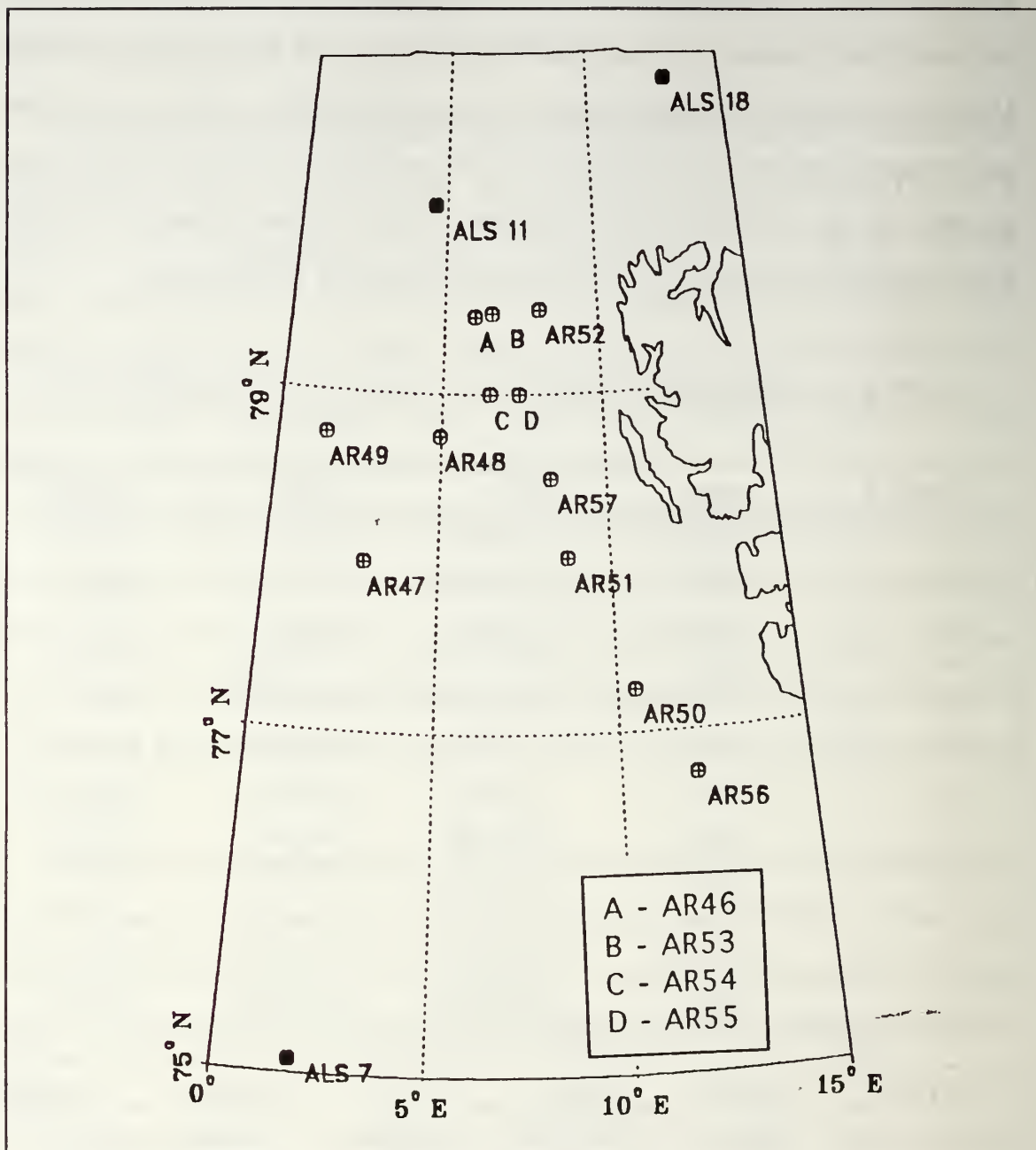


Figure 4. 1988 ALS (solid dots) and float deployment locations.

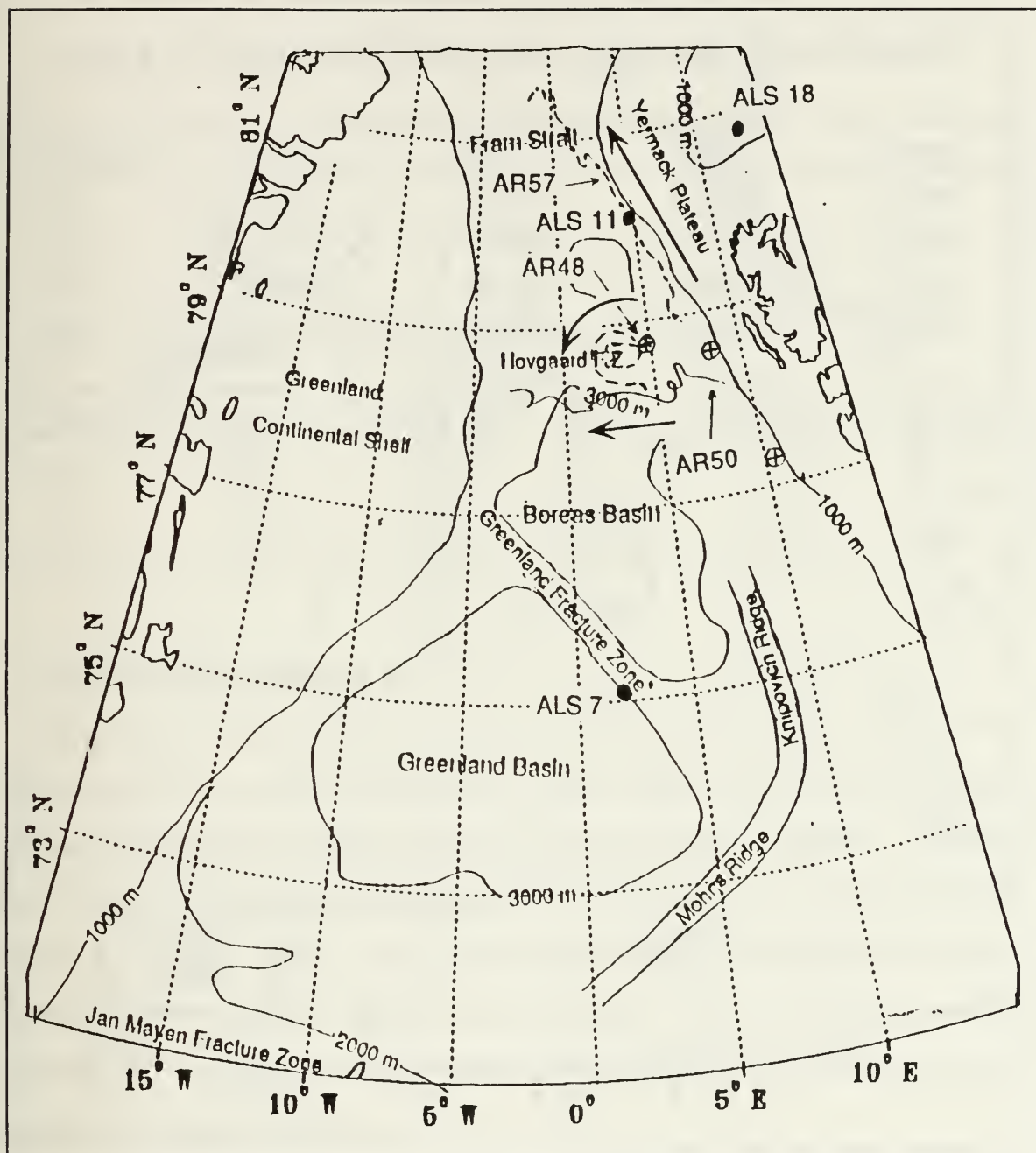


Figure 5. 1988 Trajectories of floats AR48, AR50, and AR57. The launch positions of the floats are indicated by circles.

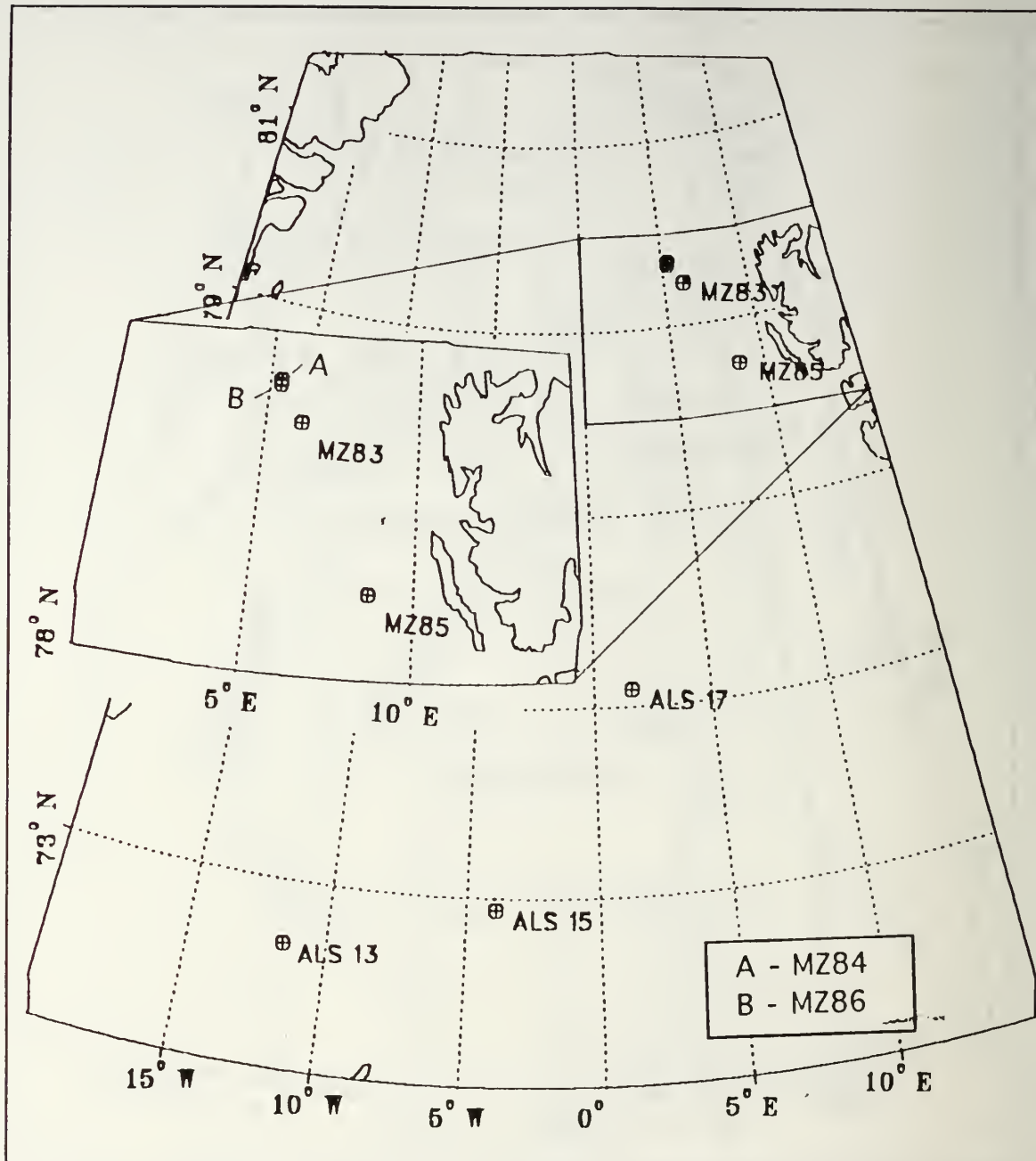


Figure 6. 1989 ALS and float deployment locations.

**TABLE 2. DETAILS OF 1989 FLOAT AND ALS DEPLOYMENTS**

| Float # | Depth     | LAT      | LON     | Launch  |
|---------|-----------|----------|---------|---------|
| 83      | 200 m     | 79 28.2N | 6 10.8E | 4/14/89 |
| 84      | 200 m     | 79 42.7N | 5 22.2E | 4/14/89 |
| 85      | 200 m     | 78 30.7N | 8 38.5E | 5/17/89 |
| 86      | 200-500 m | 79 40.9N | 5 21.6E | 4/14/89 |

| ALS # | Depth | LAT      | LON      | Launch  | Recover |
|-------|-------|----------|----------|---------|---------|
| 13    | 700 m | 72 20.9N | 11 33.7W | 9/14/89 | 8/10/90 |
| 15    | 740 m | 72 53.2N | 3 54.2W  | 9/19/89 | 8/16/90 |
| 17    | 757 m | 75 11.5N | 1 37.3E  | 9/9/89  | 8/5/90  |

## A. DATA PROCESSING

Raw plots of the 1989 ALS data, showing signal strength versus time, indicated that three floats launched in 1988 (AR48, AR50, and AR57) had adequate information to allow tracking during the 1989 deployment. The raw data also showed strong signals from two floats deployed in the spring of 1989, MZ83 and MZ86. Figure 7 is a sample record typical of these raw data plots. This plot shows received signals from four floats. A plot of the floats tracked showing the time periods of the tracking during the entire 1989 ALS deployment period is provided in Figure 8.

The raw ALS data, i.e., the recorded time of arrival of the float signal at an ALS, was processed using software provided by LODYC. The processing is accomplished in three steps using seven programs. In the first step additional data files are created which are used in later processing. In the second step each



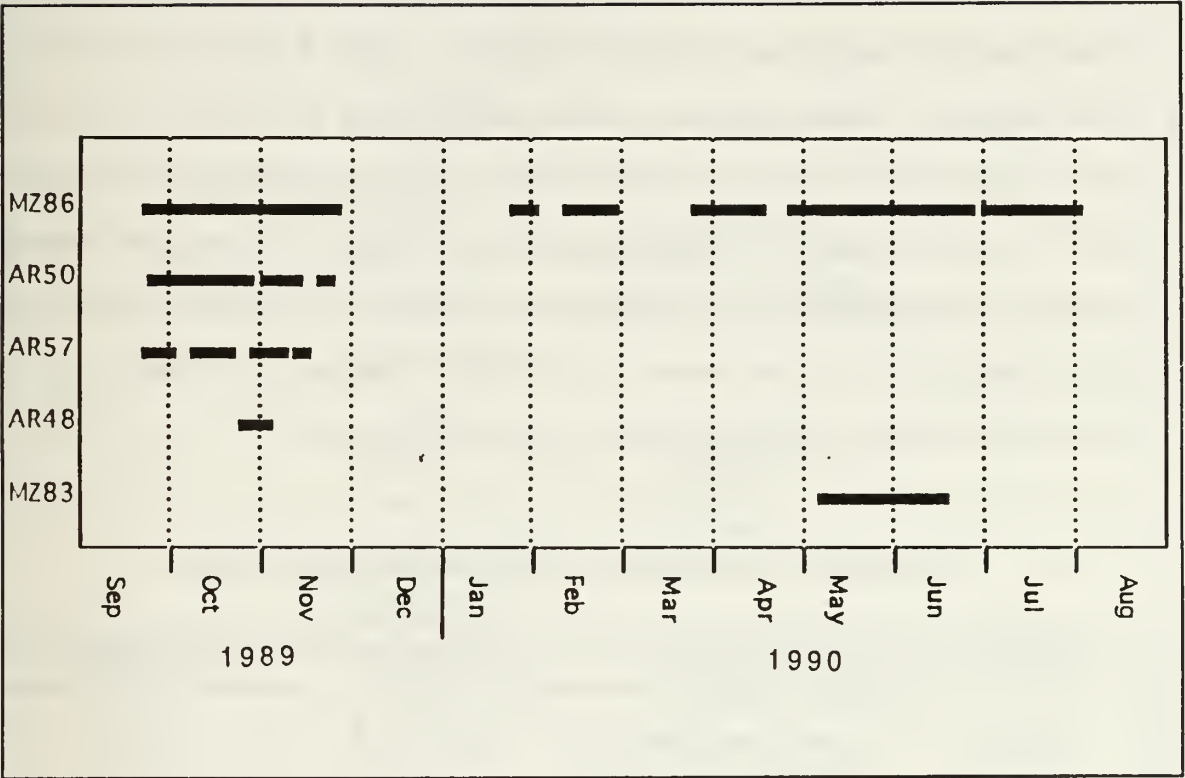


Figure 8. Bar chart showing time periods each float was tracked during the 1989 ALS deployment.

ALS data file is treated separately, extracting the signal of a particular float and interpolating to fill short data gaps. Step three brings together the data from three ALSs to calculate the clock drift for the float and ultimately calculate its position. A flow chart of a sample run is shown in Figure 9. Table 3 provides an overview of the programs. These programs were initially written by LODYC to run on a SUN 3 workstation. With one exception, the programs were recompiled to run on a SUN 4 workstation at the Naval Postgraduate School. The program **mansig** could not be recompiled; one of its subroutines, **curses**, is machine specific to the SUN 3 and could not be converted to the SUN 4. The program **mansig** was run on a SUN 3 courtesy of the Computer Sciences Department.

**TABLE 3. PROGRAM FUNCTIONS AND FILES.**

| Program  | Description                                                 | files created | files used                   |
|----------|-------------------------------------------------------------|---------------|------------------------------|
| alsentry | used to create data files for ALS and float deployment info | .FLT .ALS     | none                         |
| mansig   | extracts data for a specific float from the raw ALS data    | .TOA          | .FLT .ALS .data              |
| flterp   | interpolates .TOA file to fill data gaps                    | .INT          | .TOA                         |
| flind    | calculates float clock drift                                | .CLK          | .FLT, .ALS, .INT             |
| clkdrft  | writes the calculated float clock drift to the .FLT file    | none          | .CLK, .FLT                   |
| flind    | calculates float positions                                  | .POS          | DIRINT.DAT, .INT, .FLT, .ALS |
| toflt    | formats the final position file                             | .PRI          | .POS                         |

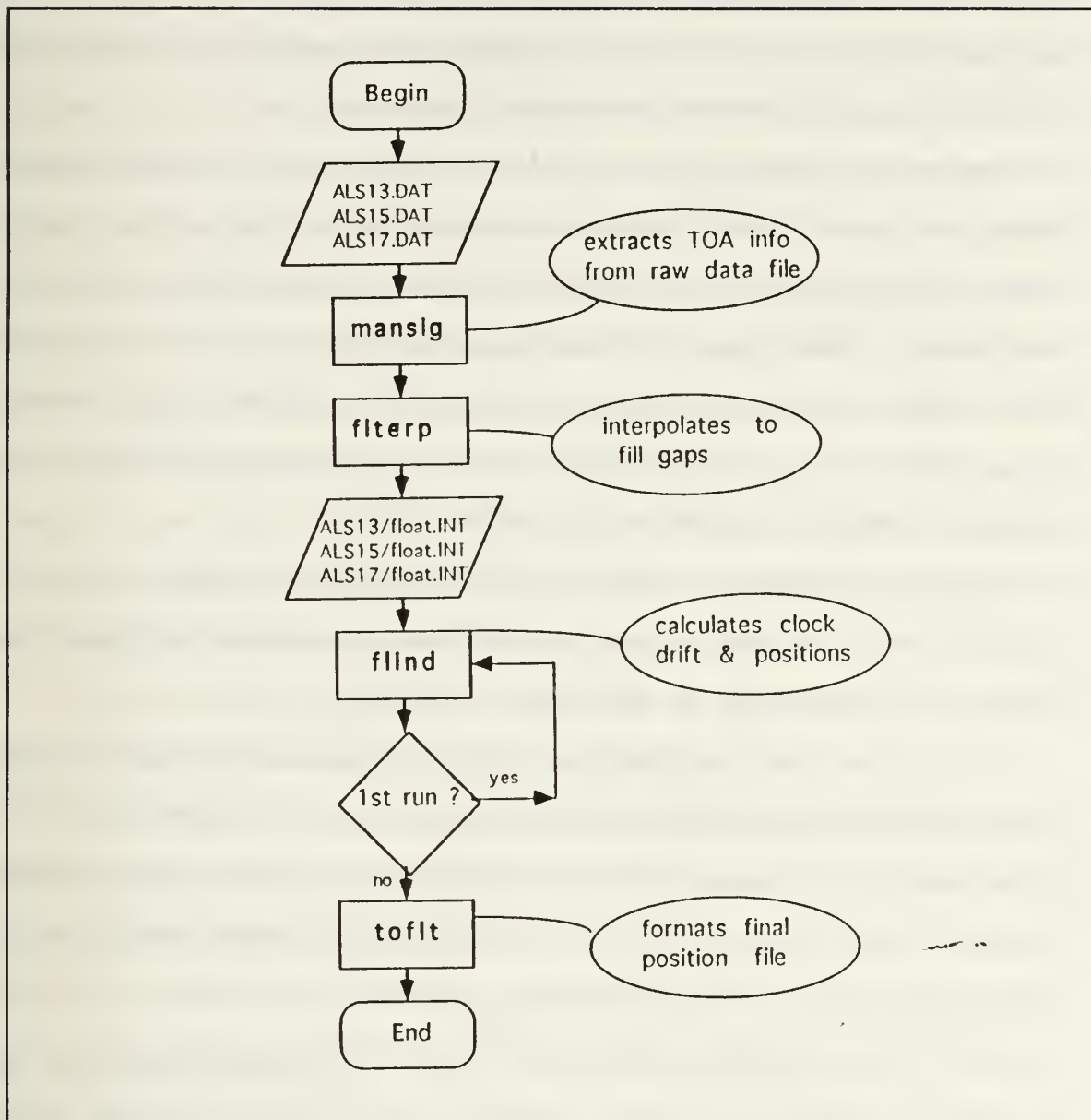


Figure 9. Processing flow chart.

The program **alsentry** creates two data files used in later processing. These files contain information on the deployment characteristics of each float and each ALS. Files with the suffix of .ALS contain the location, date of deployment, depth, and measured internal clock drift information for each ALS. The files with a .FLT suffix contain the same information for each float.

The program **mansig** applies the ALS clock drift to the raw ALS data and tracks the signal of each float as received by the ALS. This program automatically tracks the received signals based on an allowable time differential between consecutive signals. If more than one signal is received in the allotted time window, the operator must select between the available signals. **Mansig** outputs a file of time of arrivals (TOAs) for the signal of each float as received by each ALS. This file is identified with the suffix of .TOA.

The program **flterp** checks the .TOA file for possible bad points, asks the user to approve each questionable point and does a linear interpolation of all gaps less than 5 days. **Flterp** creates an interpolated (.INT) file.

The program **flind** calculates the drift of the float's internal clock and the incremental positions of the float. **Flind** needs an input file DIRINT.DAT. This file, created in an editor, is a list of the .INT files used in determining the float positions. **Flind** must be run twice; the first run is to compute the drift of the float's internal clock. The program **clkdrft** applies this clock drift to the .FLT file for use in later processing. The second run of **flind** determines the float incremental positions using the calculated clock drift for the float. Since distances are related to TOA by the mean sound speed along the path, a typical sound speed is required. **Flind** uses a default sound speed of  $1.495 \text{ km sec}^{-1}$ . However, assuming a mean temperature of  $2^\circ \text{ C}$  and a mean salinity of 34.8 PSU,

a value of  $1.46 \text{ km sec}^{-1}$  was selected as being more representative of the actual conditions in the deployment area.

A float position is computed within **flind** by using the first two arrival times to establish an initial area of probability from the intersections of distance arcs from two ALS mooring positions. The distances are determined by multiplying the time difference between the TOA at the ALS and the scheduled float transmit time by the estimated speed of sound. For two distance arcs there are two possible solutions, one on each side of the ALS baseline. The resolution of this position ambiguity is done by using a third distance arc from another ALS, if available, or by choosing the intersection closest to the last good fix. A quasi-Newtonian fit is then applied to minimize the sum of the least squares error from the calculated position to each ALS. If the rms error is greater than 10 km, then low quality TOAs are excluded and the minimization continues. The output of this program is a raw position file with the suffix .POS file. (*Gascard, 1990*)

The last program **toflt** converts the .POS file of raw positions into the final output positions in latitude and longitude, a .PRI file.

The positions were then smoothed in latitude and longitude, using an IMSL cubic spline error detection (CSSED) scheme. A sample plot of raw data and smoothed data is provided in Figure 10.

## B. PROGRAM ERRORS

The initial runs for float MZ86 showed an improbable trajectory with the float drifting onto the Greenland continental shelf in waters  $< 300 \text{ m}$  and through Shannon Island (Figure 11). It was obvious that this was not a realistic solution. A detailed review of the processing procedure was done, comparing runs using

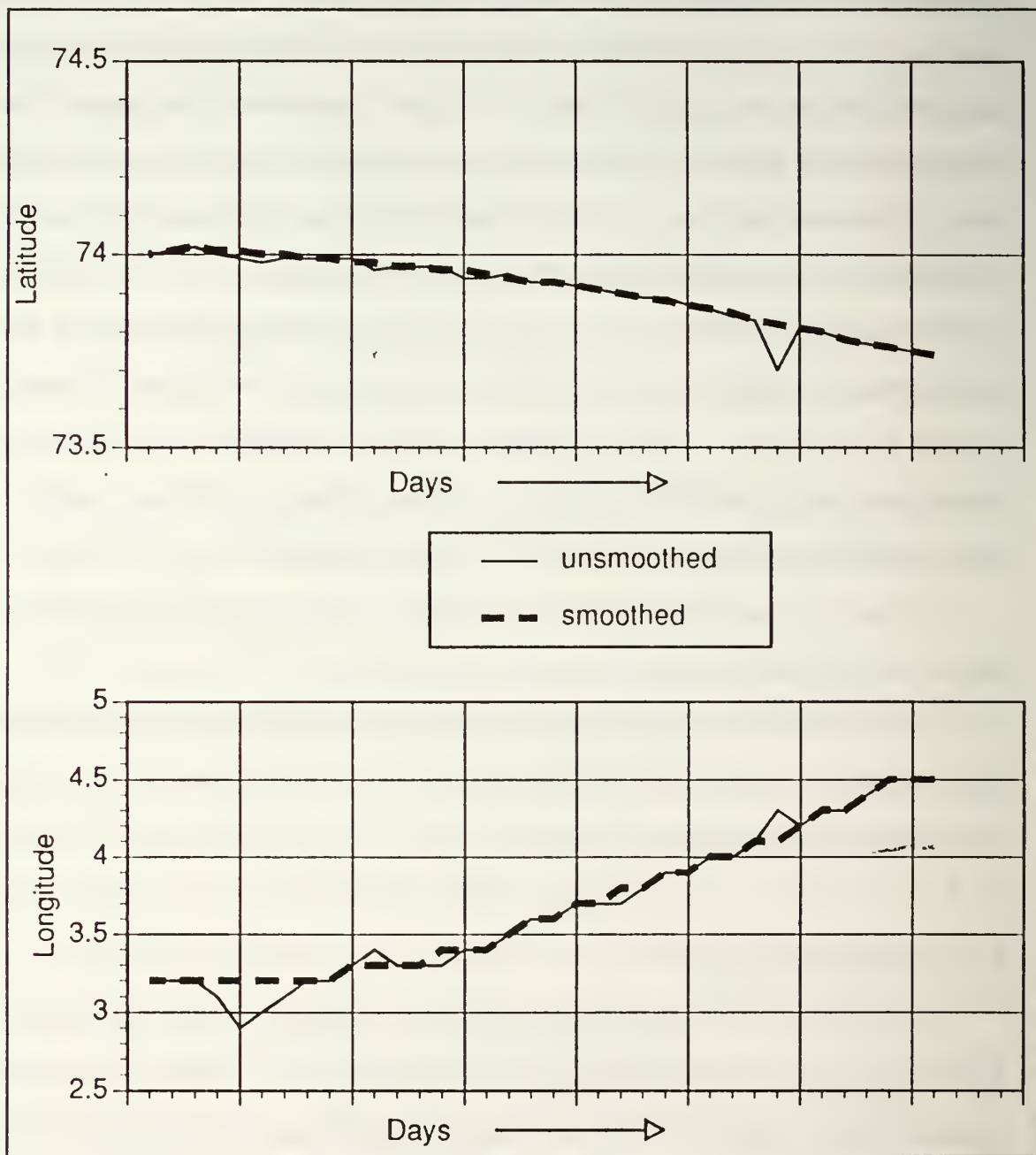


Figure 10. Results of cubic spline smoothing.

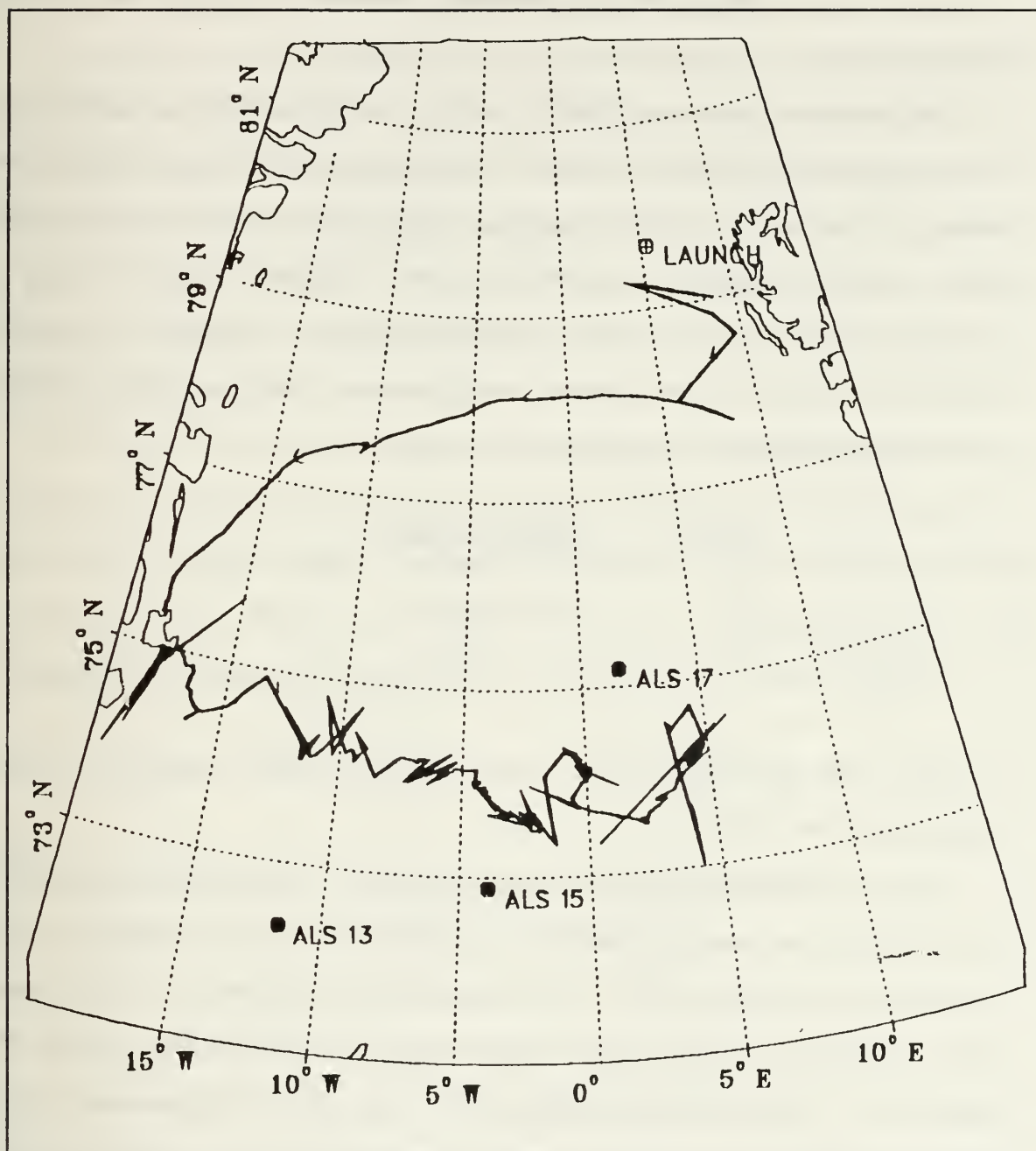


Figure 11. Plot of float MZ86 with the improperly applied ALS 17 clock drift.

different parameters in a search for a clue to the error which could cause this bad tracking. It was ultimately tied to improperly applying the ALS clock drift as described below.

The position calculation in **flind** is based on the TOA of the float signal at the ALS. Both the float and the ALSs have internal clocks which may be subject to drifting, in some cases appreciably during a year's deployment. Hence, the clock drift of each float and ALS must be determined. The clock drift of the ALS is measured when it is recovered and is applied linearly through the program **mansig** to the raw TOA file when extracting the data. The three 1989 ALSs had the following clock drifts over their deployments :

| <u>ALS</u> | <u>clock drift (secs)</u> |
|------------|---------------------------|
| 13         | +0.58                     |
| 15         | -5.15                     |
| 17         | -153.5                    |

As can be seen, the drift for ALS 17 was more than 2 orders of magnitude greater than the other two ALSs.

Two runs of **mansig** were performed on the ALS 17 data against float MZ86. One run was done using the measured clock drift for ALS 17; another run was done using a zero clock drift. It was expected that these two runs would have TOAs differing by the clock drift applied linearly over the duration of ALS 17's deployment. TOAs in early October (one month into the deployment) were expected to differ by only about 13 seconds but were found to be different by 65 seconds. Realizing that MZ86 was deployed in April 1989 and that ALS 17 was

deployed in September 1989, 5 months apart, it was apparent that five months at 13 seconds per month resulted in a drift error of 65 seconds.

From this it was determined that the program **mansig** was applying the ALS clock drift, not from the beginning of the ALS deployment as required, but from the beginning of the float deployment. In this case, with the float deployed five months prior to the ALS deployment and ALS 17 having such a large clock drift, a large error in TOA resulted. For the 1988 floats deployed a full year prior to deployment of ALS 17 the accumulated error of the clock drifts at the end of the ALS deployment would be on the order of three minutes.

To correct for this error **mansig** was rerun to extract the TOA information for each float against each ALS with the ALS clock drift set to zero. A program was then written to properly apply the clock drift to the .TOA file for the deployment period of the ALS. Figure 12 is a plot of MZ86 with this correction applied. All subsequent processing then continued as before using this corrected data file.

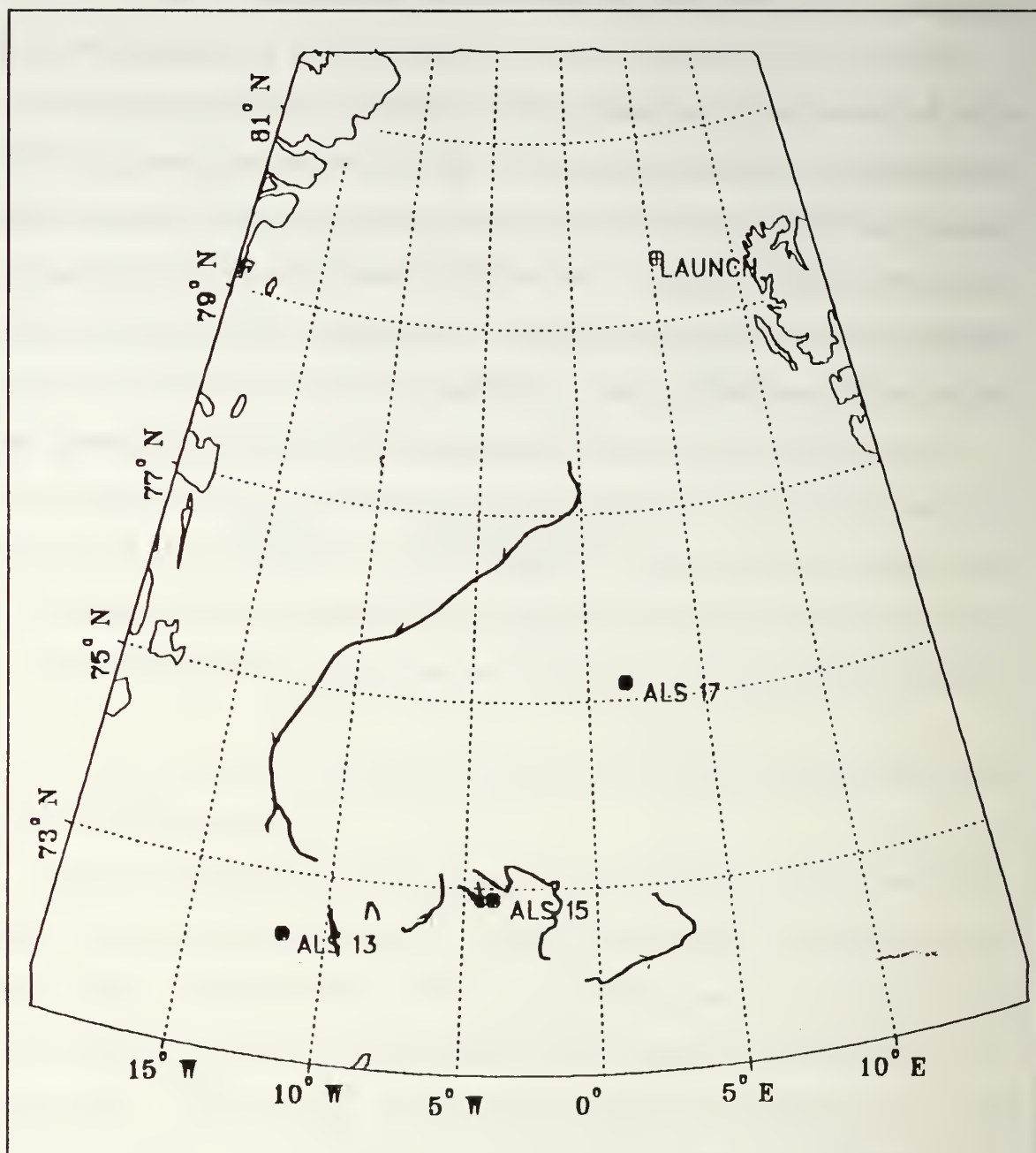


Figure 12. Plot of float MZ86 with the ALS 17 clock drift applied correctly.

### III. RESULTS

Plots of the raw 1989 ALS data indicated that signals from five floats had adequate signal strength and record length to provide useful tracking. Three of the twelve floats launched in Fram Strait in 1988 were tracked during the period from September to November 1990. Two of the four MZ floats launched in the spring of 1989 were tracked, one for over ten months while the other float tracked for a short period in the spring of 1990. The tracking results are summarized in Table 4.

**TABLE 4. DURATION OF FLOATS TRACKED DURING 1989 BY THE SOUTHERN ALS ARRAY.**

| Float | Begin Tracking | Lose Tracking | Duration (days) |
|-------|----------------|---------------|-----------------|
| MZ86  | 27 Sept 89     | 4 Aug 90      | 312             |
| AR50  | 24 Sept 89     | 25 Nov 89     | 62              |
| AR57  | 22 Sept 89     | 19 Nov 89     | 58              |
| AR48  | 26 Oct 89      | 1 Nov 89      | 5               |
| MZ83  | 9 May 90       | 3 Jun 90      | 28              |

#### A. MZ86

Float MZ86 was launched on 14 May 1989 into the waters of the WSC over the continental shelf break off the west coast of Spitsbergen. This float was tracked for a longer period of time and with a better signal strength than any other float examined in this study. It was tracked from late September 1989

through August 1990 but with several short breaks in the record possibly due to topographic blockage of the signal. A plot of the entire track along with its hypothesized track in summer 1989, prior to its acquisition five months later, is shown in Figure 13. The hypothesized track, shown as a dotted line, is based on a previous analysis of the drift pattern of SOFAR floats launched and tracked in this area during the MIZEX 84 experiment (*Gascard et al.*, 1988). Figure 14 suggests two possible drift paths, one to the northwest along the western margin of the Yermack Plateau and one to the west or southwest through the complex series of eddies associated with the Molloy Fracture Zone. The track to the northwest was chosen because of the similar placement of MZ86 to AR57 relative to the Spitsbergen continental shelf. The proposed track is an approximation to the track taken by AR57. A speed of  $3.6 \text{ cm s}^{-1}$  would be required for the float to follow the proposed track of Figure 13.

The horizontal velocities between each position suggest three different current regimes as shown in Figure 15 and summarized in Table 5. These individual regimes are shown in Figure 13 as legs 1, 2, and 3.

**TABLE 5. DETAILS OF THE INDIVIDUAL MZ86 TRACKING LEGS.**

| Leg | Start     | End       | Avg. Speed                     |
|-----|-----------|-----------|--------------------------------|
| 1   | 27 Sep 89 | 9 Oct 89  | $17 \text{ cm s}^{-1}$         |
| 2   | 10 Oct 89 | 25 Oct 89 | $28 \text{ cm s}^{-1}$         |
| 3   | 26 Oct 89 | 3 Aug 90  | $3\text{-}5 \text{ cm s}^{-1}$ |

MZ86 was tracked in late September moving south through the center of the Boreas Basin, shown in Figure 13 as leg 1, with an average velocity of  $17 \text{ cm s}^{-1}$ .

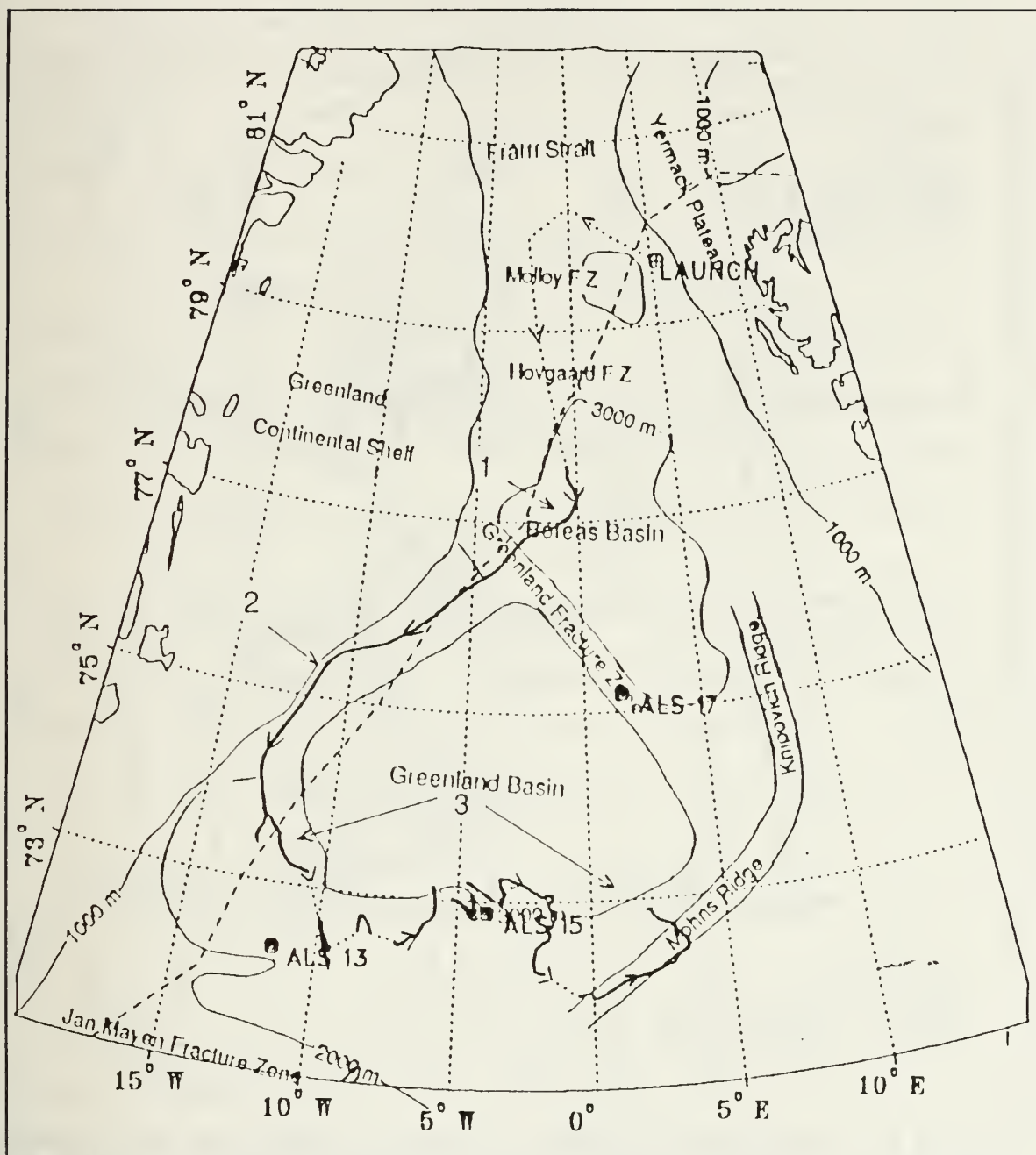


Figure 13. Trajectory of float MZ86. The dotted line represents an estimated track between launch and the beginning of tracking; the dashed line is the approximate position of the ice edge during 1-30 October 1990.

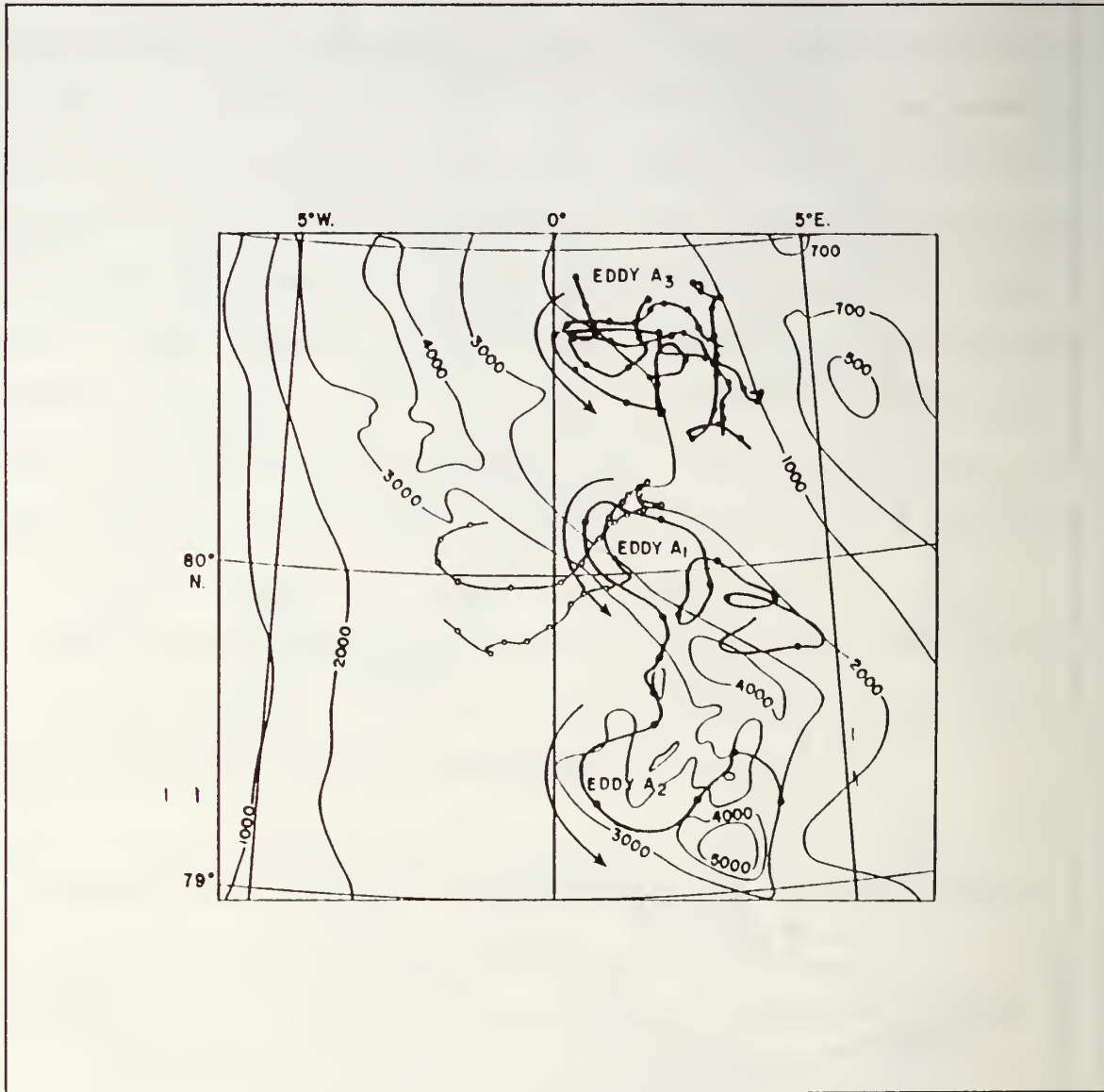


Figure 14. Two SOFAR float drift tracks during MIZEX 84. Dots represent positions every other day. Open circles represent the track of a MIZEX 83 surface drifter (from *Gascard et al.*, 1988).

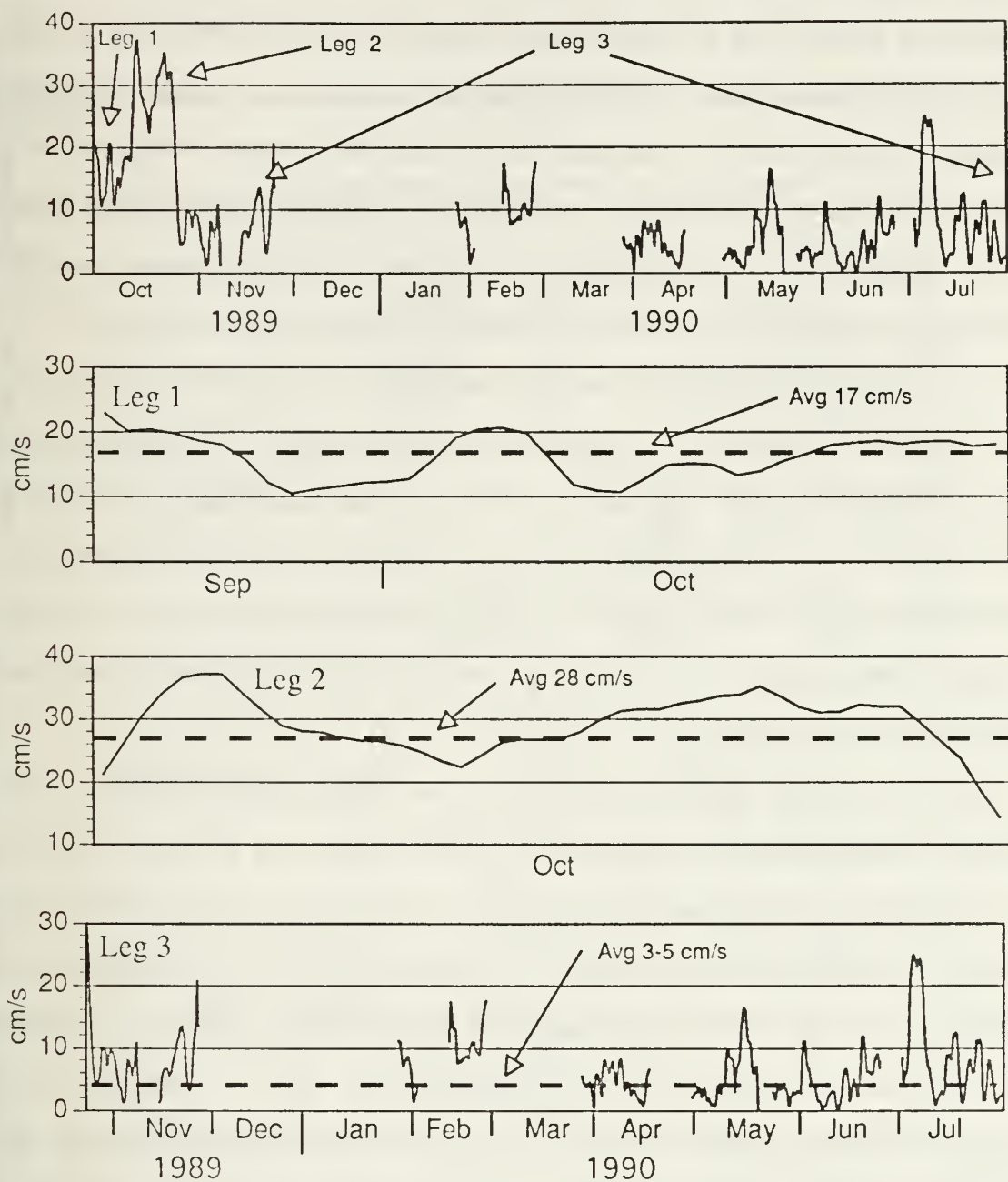


Figure 15. Velocity series for MZ86 from 27 September 1989 to 3 August 1990. Top panel shows overall track while the lower panels show the speeds during legs 1, 2, and 3, respectively.

This speed agrees well with that of *Muench et al.* (1986) who reported current velocities of 10 to 15 cm s<sup>-1</sup> from current meters at 420 m depth in the western margin of the Boreas Basin. The float continued southwest across the Greenland Fracture Zone and onto the continental slope. The *GSP Group* (1989) reported a satellite-tracked buoy, drogued at 30 m, on almost an identical track (Figure 16) as part of MIZEX '87. This suggests that the near-surface currents and the intermediate currents in this area are coupled as far as direction is concerned.

As MZ86 approached the Greenland continental shelf at about 76.8°N, its speed increased to 28 cm s<sup>-1</sup> and followed the margin of the Greenland Continental Shelf (leg 2). It continued along the shelf break but upon reaching 75.5°N tracked more southerly. *Bourke et al.* (1987) showed that currents over the Greenland shelf break in this region can reach speeds of 34 cm s<sup>-1</sup>. These currents, related to the baroclinic EGC jet, were found to be limited to the upper 150 m as shown in Figure 17.

MZ86 was below this layer of baroclinic flow at approximately 400 m. The baroclinic contribution to the flow at 400 m was found to be less than 2 cm s<sup>-1</sup> from Figure 17. The remaining 26 cm s<sup>-1</sup> of the flow must be due to the barotropic component which is accelerated in this region by its interaction with the continental slope. This acceleration may be explained as follows. The deep flow along the continental slope is analogous to the flow in a channel on a rotating plane (*Gill*, 1982). The flow is enhanced by the balance between the Coriolis force and potential vorticity. A slope of isopycnal surfaces near the bottom indicates a baroclinic component to the flow approaching the bottom with the higher density surfaces to the right. If the width of the flow is comparable in scale to the Rossby radius of deformation, then Kelvin waves may

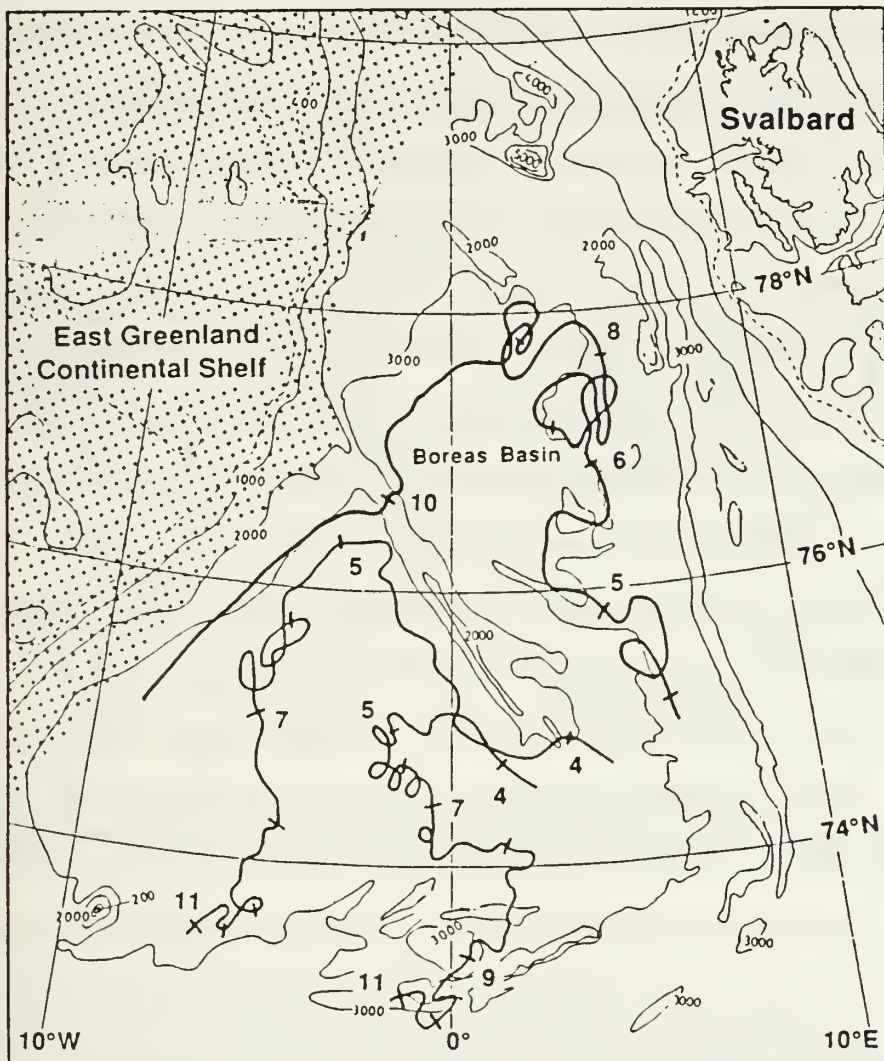


Figure 16. Trajectory of satellite tracked buoys (drogue at 30 m) from MIZEX '87 (numbers indicate date of position) (from GSP Group, 1989).

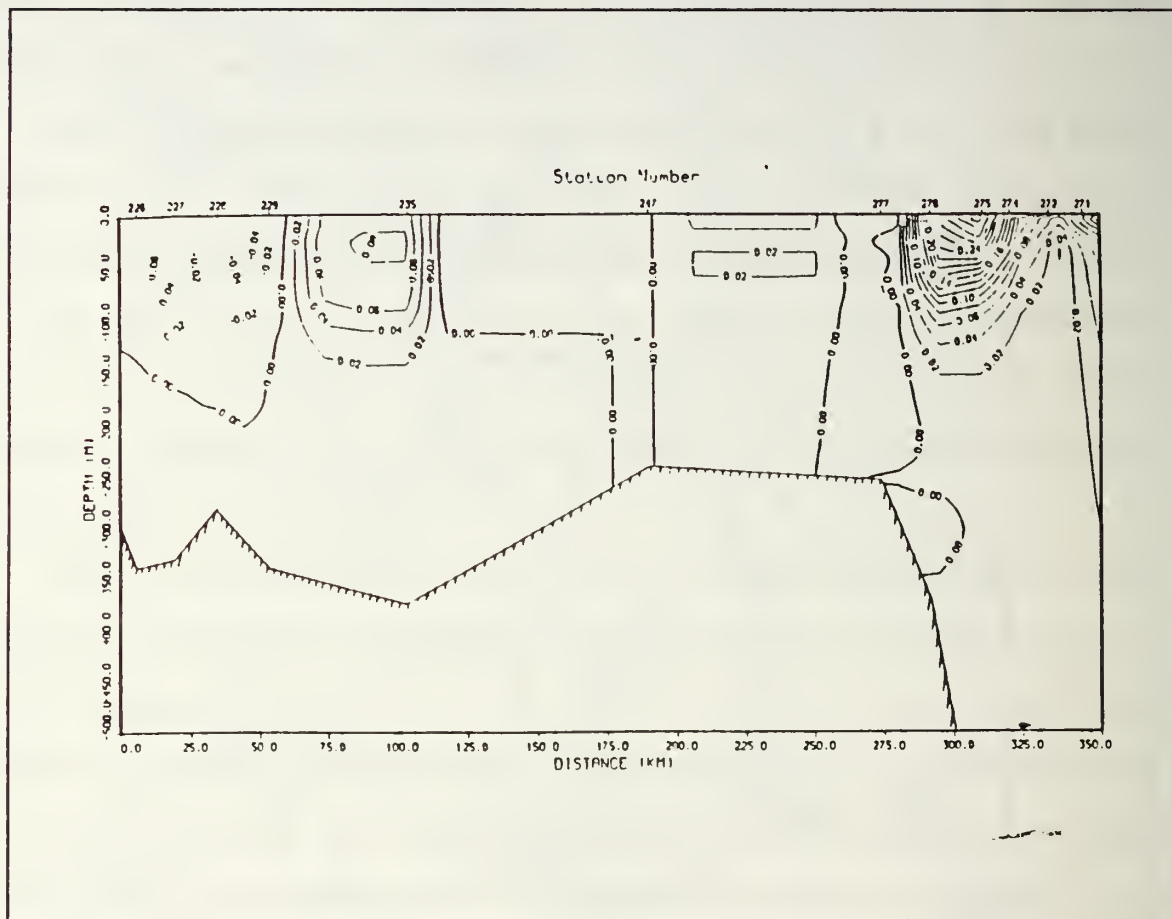


Figure 17. Vertical baroclinic current velocity section at 77.5°N (contours are in  $\text{m s}^{-1}$ ). The jet of the EGPF centered over the upper continental slope indicates speeds of up to  $34 \text{ m s}^{-1}$  (from *Bourke et al.*, 1987).

be set up traveling along the flow with the slope/boundary to the right. Aagaard (1990) described similar enhanced slope-trapped currents from current meter observations in the Arctic Basin, along the slope northeast of Svalbard. A cross section through one of these features at  $\sim 40^{\circ}\text{E}$  illustrates the presence of a high speed boundary layer current aligned with the continental slope (Figure 18). A similar boundary current was found by *Smith* (1976) at the southern limit of the EGC where it exits over the sill of the Denmark Strait. Figure 19 depicts this boundary current flow as the wedge of dense water from 200 m to the bottom with the isopycnals sloping down to the right, indicating a current out of the paper toward the reader. In this figure the surface manifestation of the EGC is shown as the wedge of lighter water at the surface on the western edge, with isopycnals sloping up to the right, again indicating flow out of the paper toward the reader. *Smith* (1976) found currents on the order of  $60\text{ cm s}^{-1}$  near the bottom, suggesting the observed barotropic velocities of  $26\text{ cm s}^{-1}$  near 400 m are reasonable. A similar feature was observed in the Meteor 82 data (*Koltermann and Lüthje*, 1989) taken farther to the north which demonstrates a similar convergence of the deep dense water up against the continental slope.

At  $74^{\circ}\text{N}$  the float began a slow turn to the east. The flow of the EGC in this region has been described in the past, most recently by *Aagaard et al.* (1991), to diverge with one component turning eastward at about  $74^{\circ}\text{N}$  and another component continuing south along the slope. The eastward component appears to be derived mostly from waters near the seaward or eastern margin of the EGC while the water closer to the slope continues to the south across the JMFZ. After turning eastward MZ86 meandered across the southern margin of the Greenland Sea (leg 3) with an average velocity of  $3\text{--}5\text{ cm s}^{-1}$ . During this leg the float was

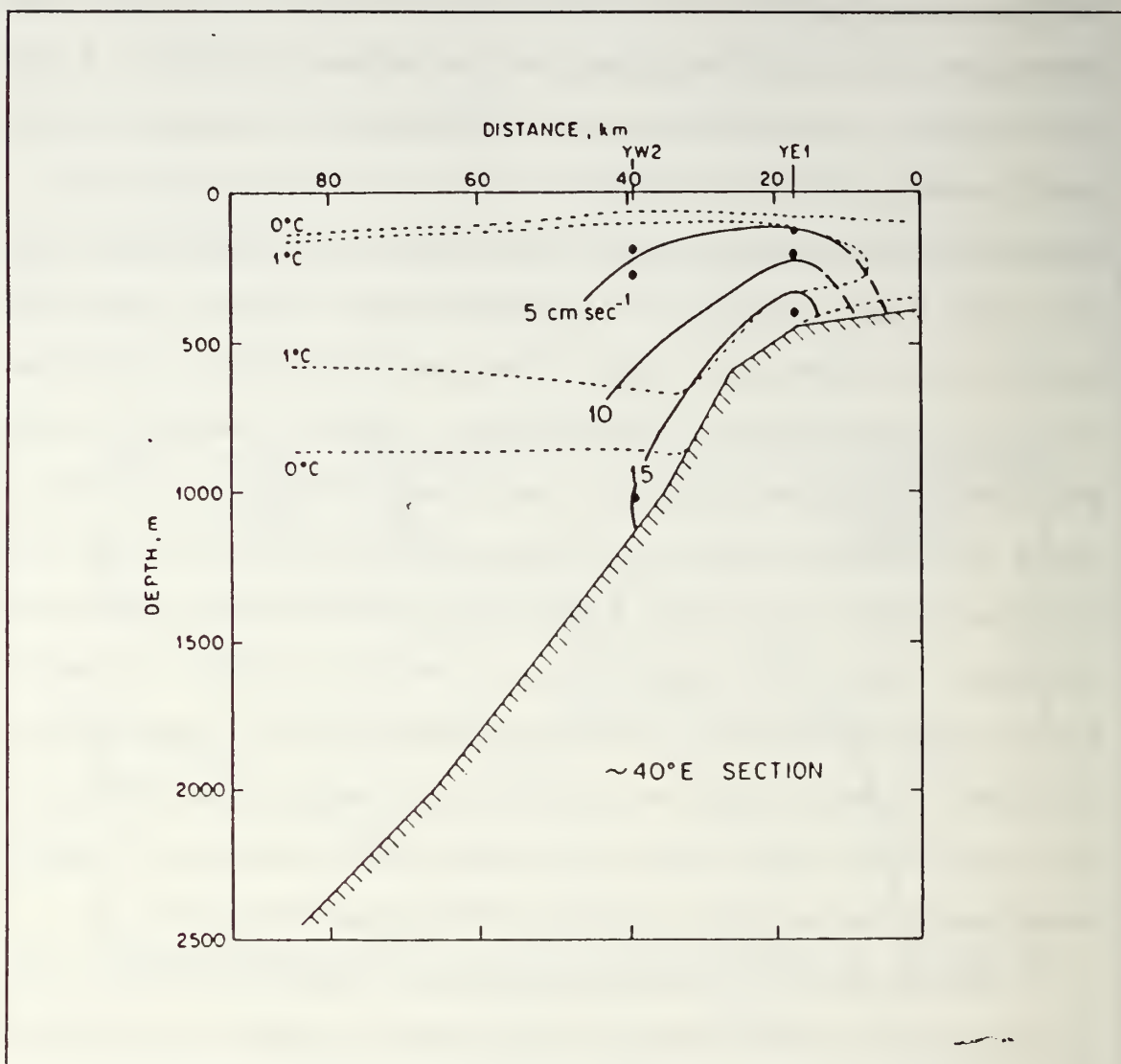


Figure 18. Section across the continental slope in the Arctic Basin showing an intensified boundary current trapped along the continental slope with the velocity increasing toward the bottom (from *Aagaard, 1989*).

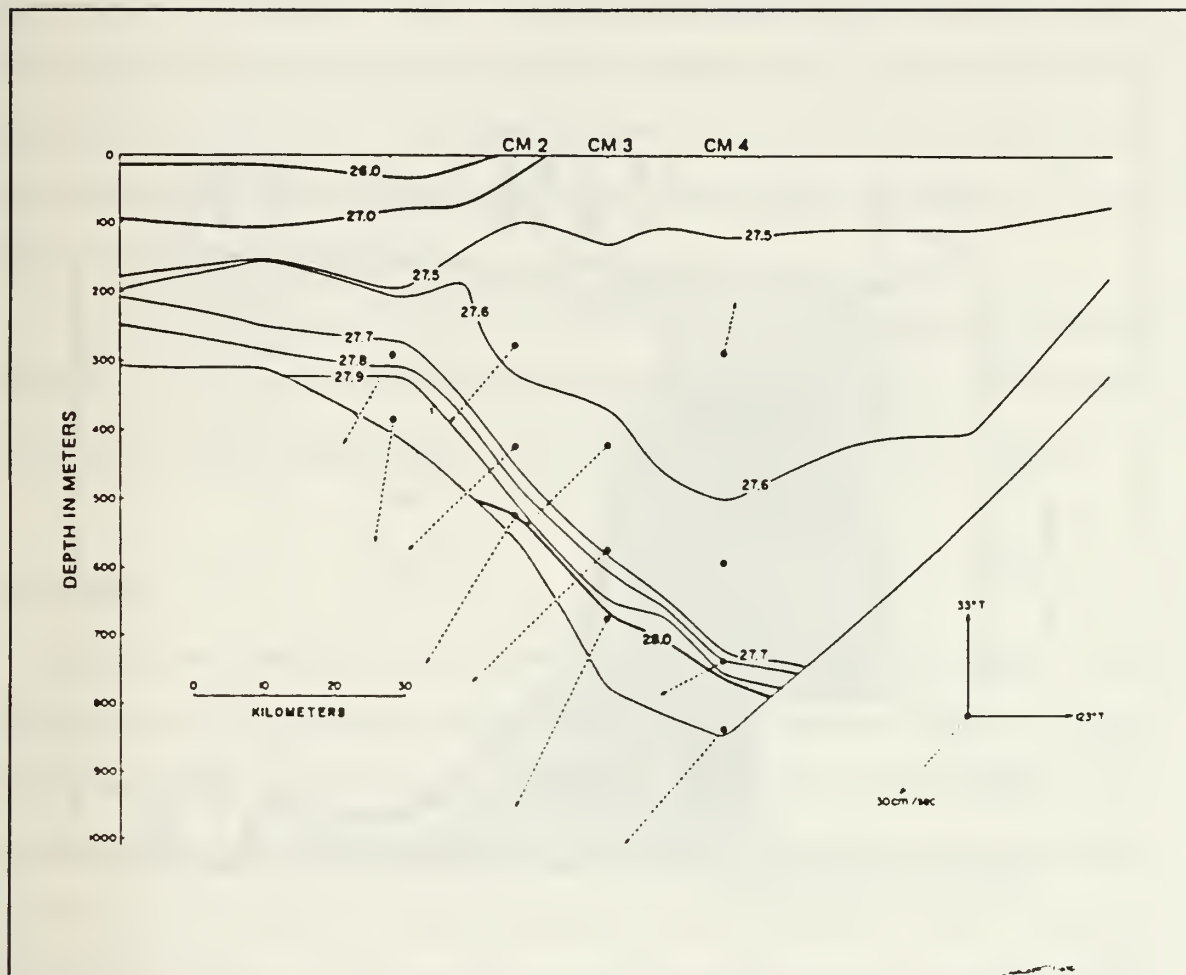


Figure 19. Vertical density ( $\sigma_t$ ) cross section across the Denmark Strait (from Smith, 1976). Dotted arrows show that measured currents near bottom are directed to the southwest and that they are accelerated as the current is forced against the continental slope.

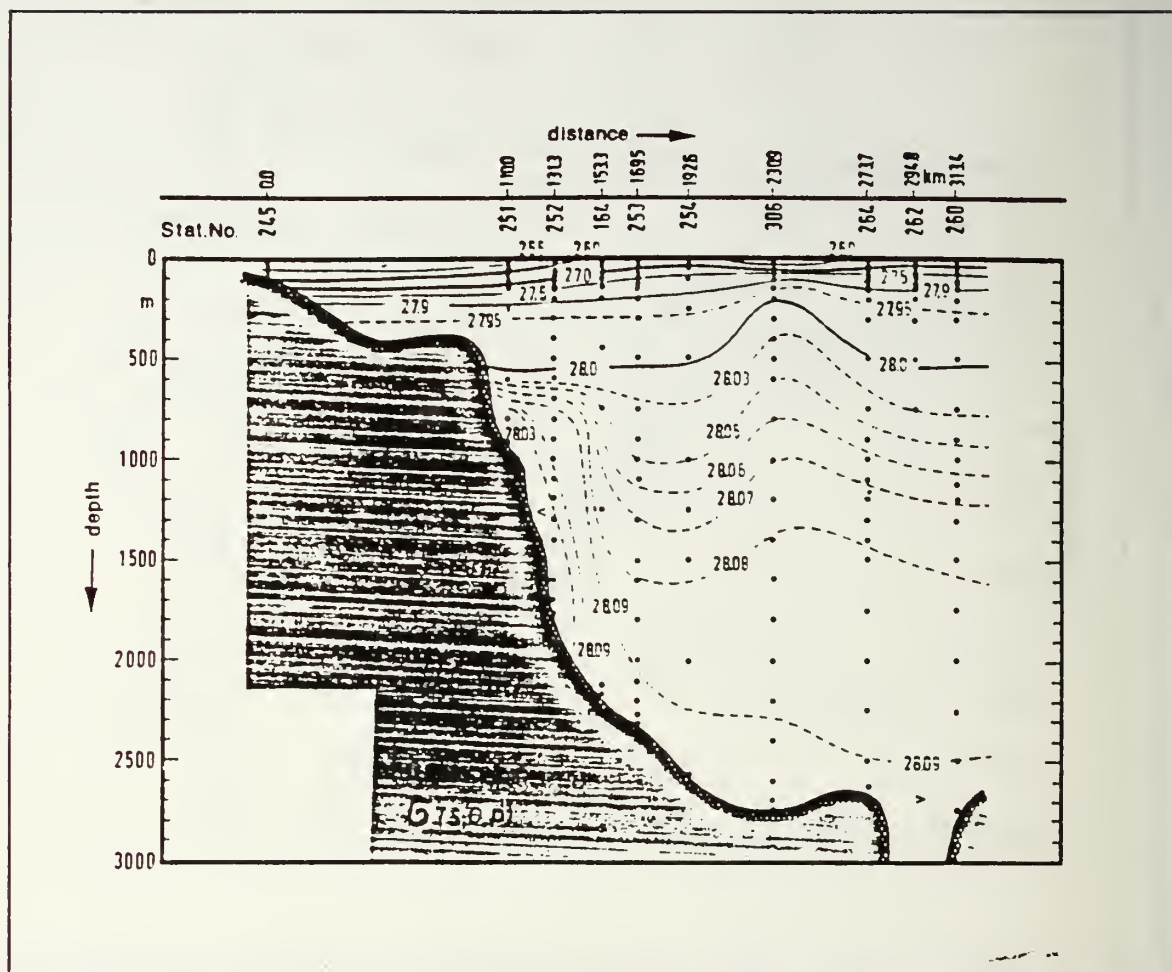


Figure 20. Cross section at 79°N showing the density structure associated with the southward flowing bottom boundary current against the continental slope (from Koltermann and Lüthje, 1989).

embedded in the intermediate waters of the Jan Mayen Current and maximum speeds of more than  $20 \text{ cm s}^{-1}$  were observed. These values compare closely with observations taken from year-long (1987-1988) moored current meters (*Aagaard et al.*, 1991) which showed mean velocities of  $5.5 \text{ cm s}^{-1}$  at  $93^\circ \text{ T}$  at 220 m depth. The position of these current meters was very close to leg 3 and had an observed maximum of  $20.1 \text{ cm s}^{-1}$ . An important aspect of their data was that the velocity changed very little with depth ( $<0.5 \text{ cm s}^{-1}$  over 2500 m) indicating the strong barotropic nature of this flow.

During this easterly drift the float was caught up in various eddy-like features. It continued to the east where at  $72.5^\circ \text{ N}$  it turned to the northeast, apparently merging with a branch of the Norwegian Atlantic Current (NAC).

## B. AR50

AR50 was launched on 6 September 1988 south of Fram Strait. It was tracked from 17 September to 13 November 1988 moving west across the Boreas Basin just north of  $78^\circ \text{ N}$  (Figure 21). Contact was lost with the float near the western edge of the Boreas Basin and it remained untracked until the fall of 1989, when it was located in the southeastern part of the Greenland Sea. A possible drift path, to account for its motion during the nearly one year it was not tracked, may be deduced from the trajectory of MZ86 shown by the dotted line in Figure 21. Considering the distance involved and the time the float was not tracked an average speed of  $3.8 \text{ cm s}^{-1}$  would be required for the float to navigate this path. On 24 September 1989 contact was gained on AR50 in an area southeast of the Mohns Ridge by the southern ALS array inserted earlier in the month. It tracked northwest more or less parallel to the MZ86 track in the same area in July 1990.

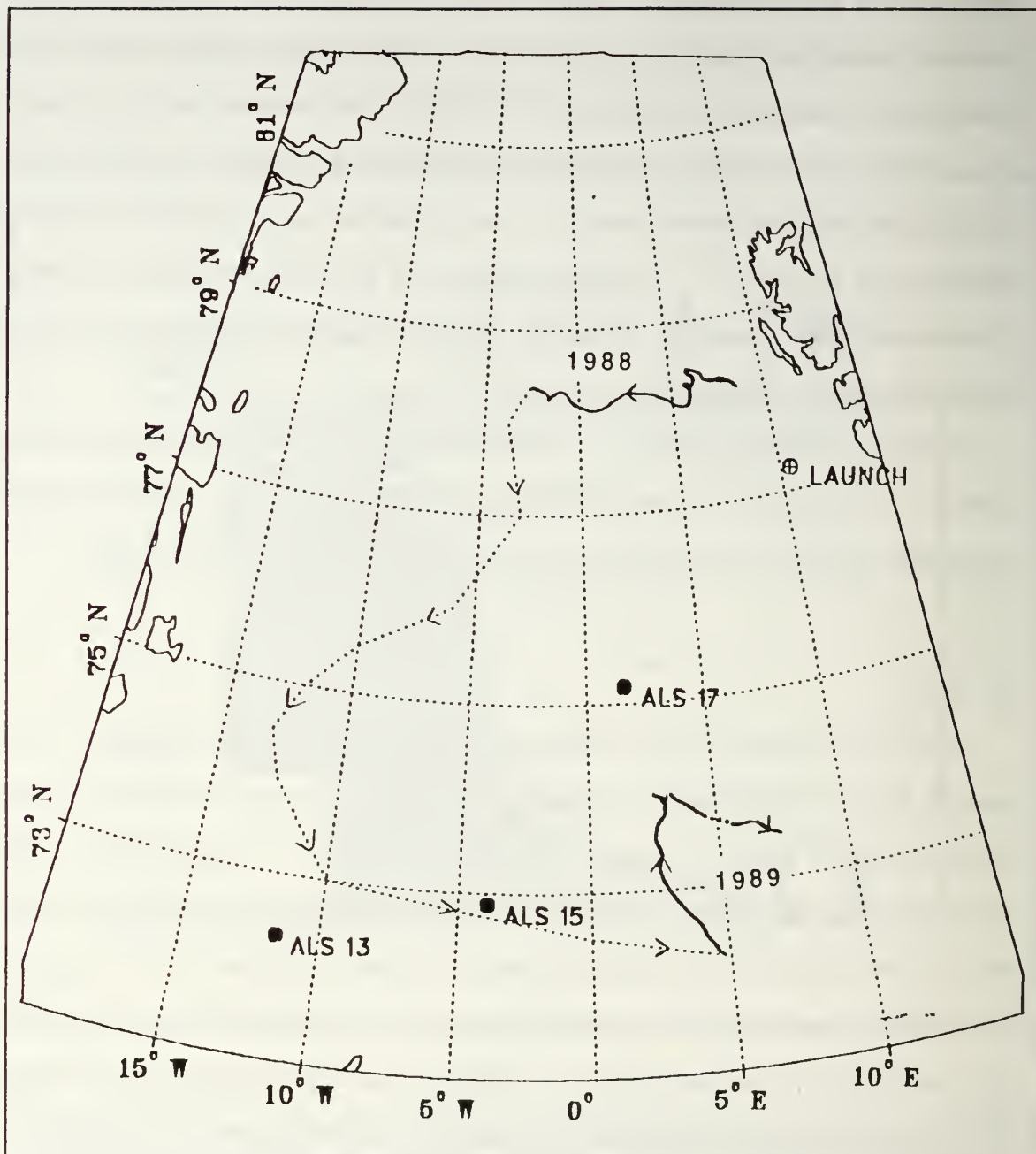


Figure 21. 1988 and 1989 trajectories of float AR50. The dotted line represents an estimated track based on the trajectory of float MZ86.

It then turned back to the southeast and recrossed Mohns Ridge where it was lost again. The path of AR50 appears almost as an extension of the MZ86 track, probably caught in a filament of the Norwegian Atlantic Current.

### C. AR57

AR57 was launched on 21 August 1988 into the waters of the WSC. It was tracked by the northern array of ALS's from 30 August to 6 December 1988 drifting to the northwest through Fram Strait and along the Yermack Plateau shelf break as shown in Figure 22. Contact was lost at approximately 81.3°N as the trajectory turned to the southwest. It remained untracked until 22 September 1989. Again, based on the MZ86 trajectory, an estimated track was made to cover the untracked period. An average velocity of  $6.2 \text{ cm s}^{-1}$  would be necessary to achieve this track. Contact was regained with the float east of Mohns Ridge. Several short tracking periods showed the float moving into the Bear Island Trough of the Barents Sea north of Norway. The nature of these short tracking periods suggests that the signal was blocked by the high relief of Mohns Ridge, with occasional periods when the float was positioned such that the signal passed through the breaks in the ridge to the moored listening stations.

### D. AR48

AR48 was launched 4 September 1988 in Fram Strait. This deep float (1065 m) was tracked from 5 September to 18 November 1988 passing through several eddies with a very slow general trend to the southeast as shown in Figure 23. AR48 was recontacted on 26 October 1989. This contact was very weak and only lasted for a five day period. The position record was not long enough to

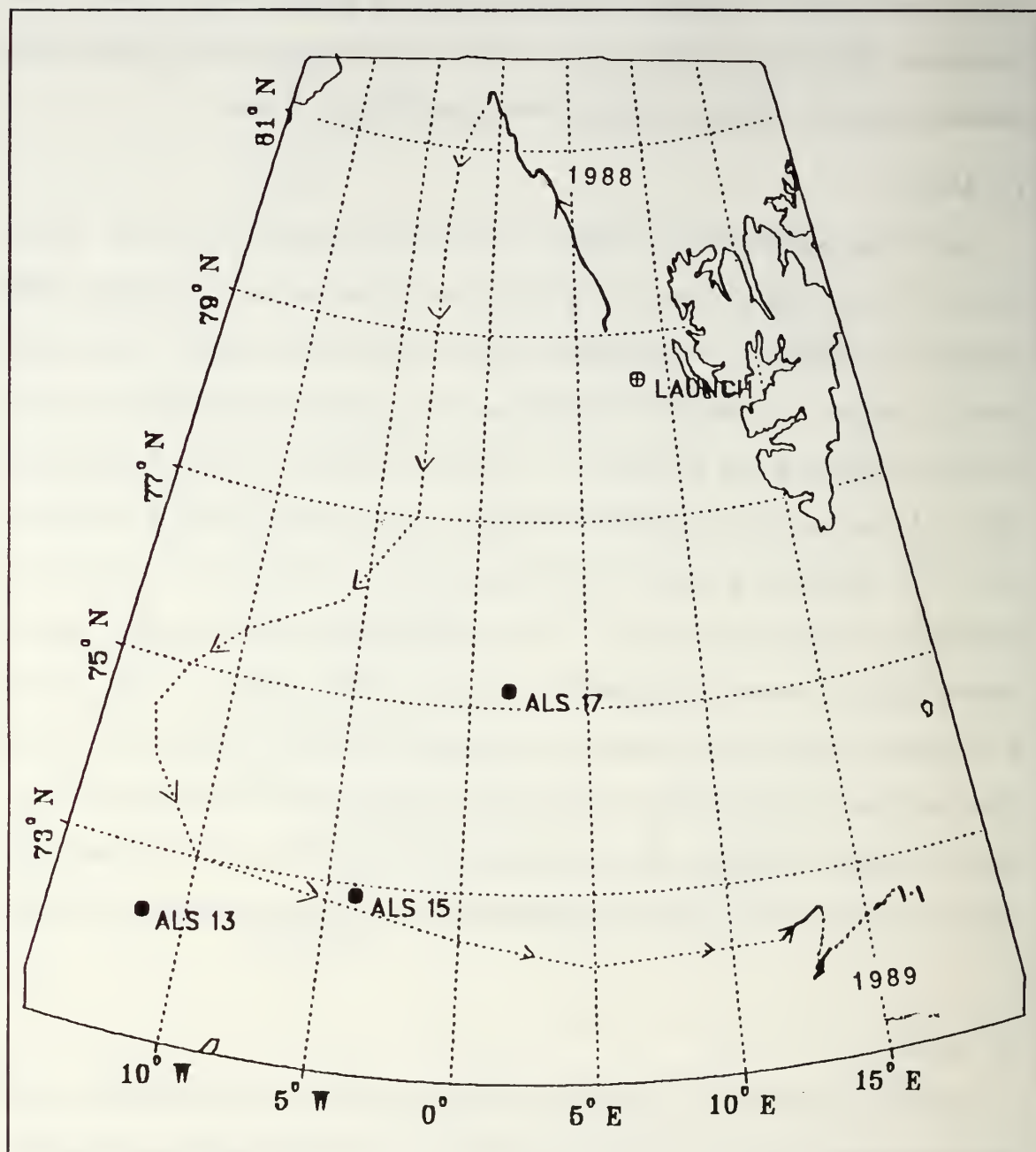


Figure 22. 1988 and 1989 trajectories of float AR57. The dotted line represents an estimated track based on the trajectory of float MZ86.

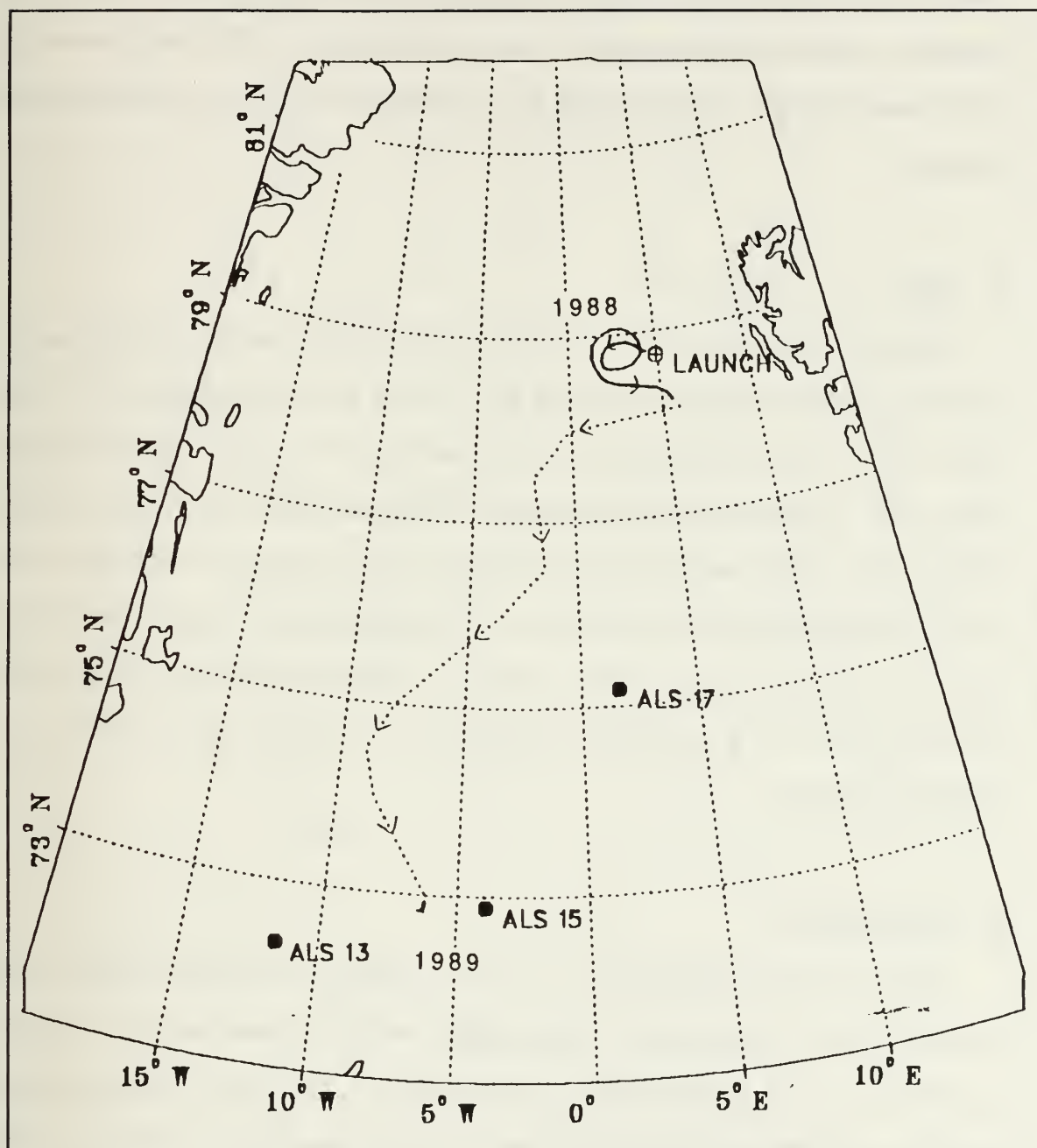


Figure 23. 1988 and 1989 trajectories of float AR48. The dotted line represents an estimated track based on the trajectory of float MZ86.

provide trajectories but was sufficient to position the float 13 months after it was launched. Again an estimated track, based on the track of MZ86 was provided to fill the tracking gap. A speed of  $2.3 \text{ cm s}^{-1}$  would be required if AR48 followed this track.

### E. MZ83

MZ83 was launched on 14 April 1989 in Fram Strait and was initially tracked by the southern ALS array 13 months later. Weak contact was gained on 9 May 1990 with the float drifting to the east-northeast in the Jan Mayen Current (Figure 24). Similarly with the tracking of AR48, this short record provides little information on the motion of the float but does provide an estimate of the distance the float must have traveled in the preceding year. Based on the time between the launch and tracking period, an estimated track to achieve that position is shown as a dotted line on Figure 24. An average speed of  $4.2 \text{ cm s}^{-1}$  would be required.

### F. DISCUSSION

These five float trajectories provide a glimpse of the intermediate depth currents of the Greenland Sea. Float MZ86, with its extensive drift trajectory, describes the path of intermediate depth waters as they exit Fram Strait and migrate around the Greenland Sea Gyre. Two additional floats, AR50 and AR57, show trajectories farther to the east beyond the end of the MZ86 track. AR48 provides a glimpse at the motion of the currents at 1000 m. All these floats, representing predominantly barotropic motion, indicate the flow path that the

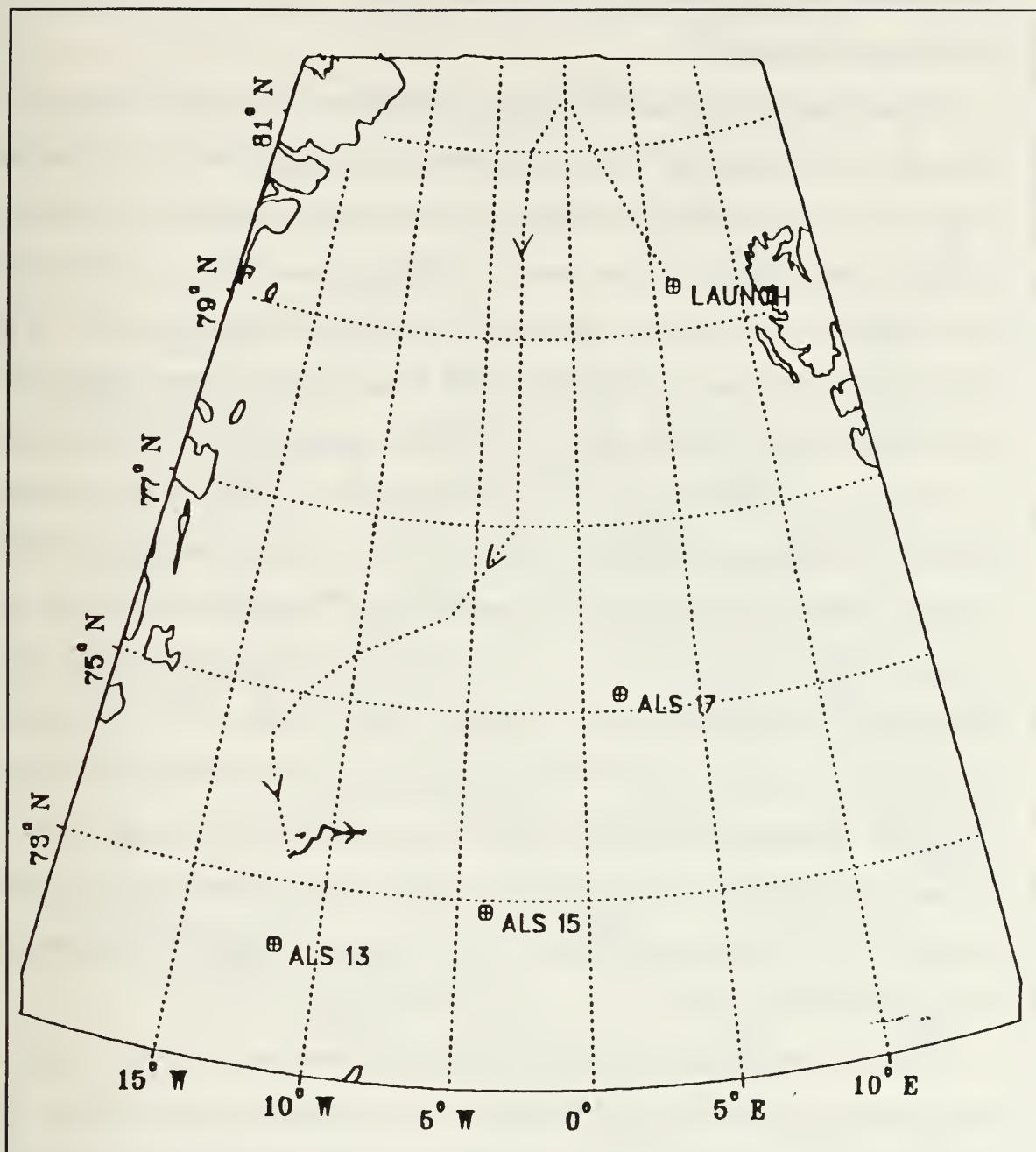


Figure 24. Launch position and tracked positions of float MZ83. The dotted line represents an estimated track based on the trajectory of float MZ86.

intermediate and deep waters most likely take as they migrate cyclonically around the Greenland Sea Gyre.

The relationship of float MZ86 to the bathymetry is provided in Figure 25. Since the variation of  $f$ , the Coriolis parameter, is very slight over the latitudinal range of this study ( $<2\%$ ), the bathymetry can be used to represent constant  $f/h$  contours. During leg 1 the float exited the central Boreas Basin in waters deeper than 3000 m and crossed the Greenland Fracture Zone on a trajectory to the southwest. On the southern side of the GFZ it was no longer over the deep floor of the basin but was located along the western boundary of the continental slope of Greenland. After crossing the GFZ the float, now at a depth of approximately 350 m, tracked through an area of relatively constant depth between the 2000 m and 3000 m isobaths. Its trajectory ultimately carried it partially up the slope as it proceeded to the southwest where its velocity was enhanced by this up slope effect and the resulting boundary current. As it crossed  $74^{\circ}\text{N}$ , its trajectory turned toward the east. The MZ86 signal was then interrupted by the Vesteris Seamount. As the float approached the seamount, ALS 17 lost contact when the ray path was disrupted by the seamount's shallow depth. Interestingly, the other two ALSs also lost contact on MZ86 at the same time. The loss of signal to these ALSs remains unexplained.

On this eastward leg in the JMC the velocity slowed to  $3\text{--}5\text{ cm s}^{-1}$  while the float traversed an area of near constant depth between 2000 m and 3000 m. The float appears to exhibit some linear oscillatory motions between  $10^{\circ}\text{W}$  and  $3^{\circ}\text{W}$  (Figure 26). These features have an approximate wave length of 40 km and an amplitude of 24 km. At present, there is insufficient data to explain the cause of the meanders. A likely candidate is that they represent fingers or filaments of the



Figure 25. Plot of tracks of MZ86, AR50, and AR57 on detailed bathymetry of the Greenland Sea.

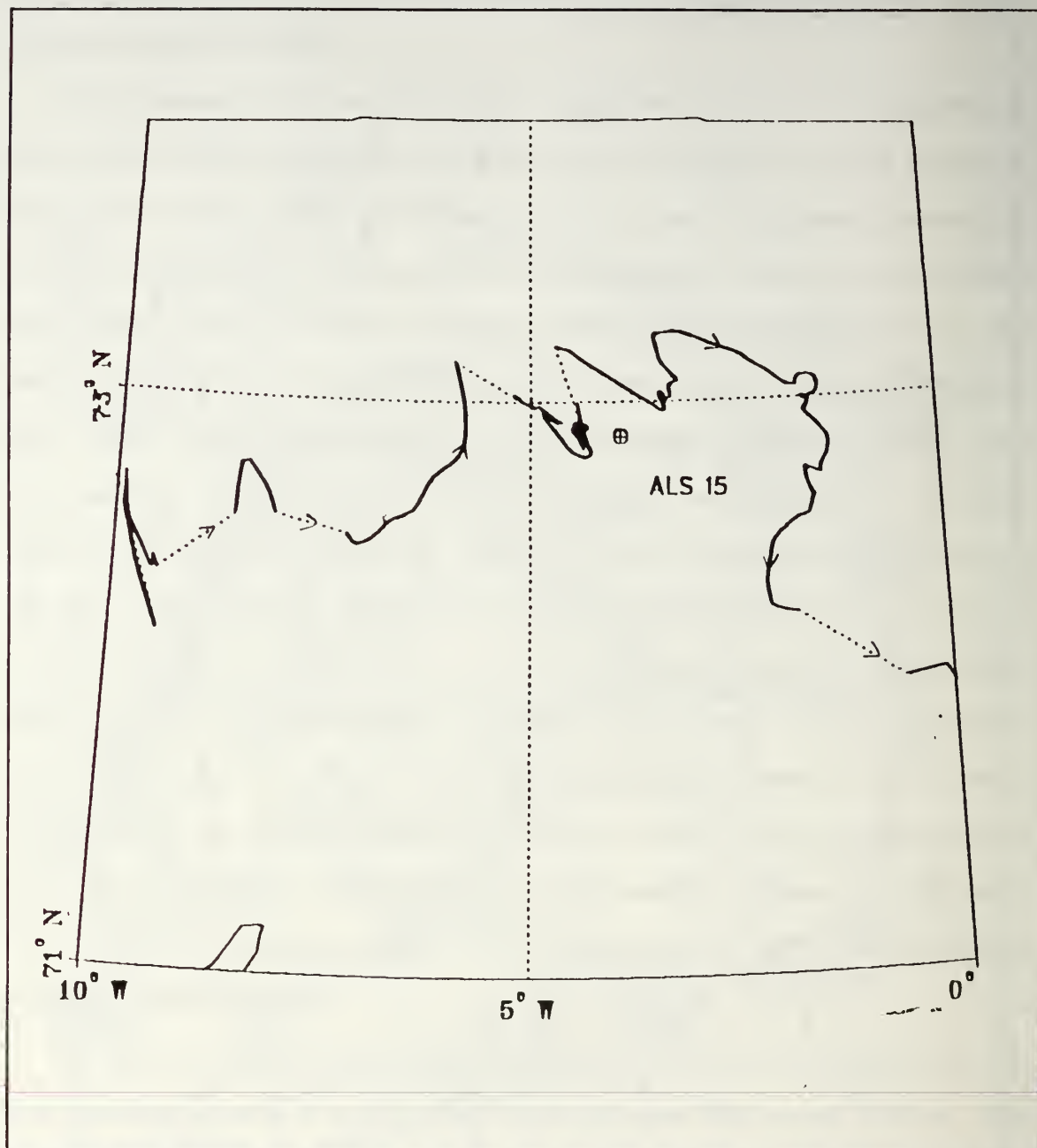


Figure 26. Detailed track of MZ86 leg 3, showing broad meanders as the float tracked to the northeast. Dotted line connects individual tracking periods.

flow that are topographically responding to the channels delineated by the breaks in the Mohns Ridge system.

At approximately  $3^{\circ}\text{W}$  the bottom becomes more complex and the track began to cross isobaths. As the trajectory approached  $2^{\circ}\text{W}$  it took a sharp turn to the south and then the southeast. In the vicinity of  $72^{\circ}\text{N}$ ,  $0^{\circ}$  the float tracked through a narrow break in Mohns Ridge and drifted along a rift valley of the ridge system. It tracked along this feature until approximately  $3.5^{\circ}\text{E}$ , whence it turned sharply to the northwest apparently caught up in a northward flowing branch of the Norwegian Atlantic Current.

During October 1989, 9 months earlier, float AR50 tracked through the same area as MZ86, crossing the Mohns Ridge slightly farther to the east. AR50 may have drifted eastward in the Jan Mayen Current, across the Greenland Sea somewhat to the south of the MZ86 track. An interannual north-south shift in the axis of the flow of the JMC has been noted by *Bourke et al.* (1991). AR50 continued tracking to the north-northwest to  $74^{\circ}\text{N}$  whereupon it turned sharply to the southeast and recrossed the ridge apparently following gaps in the ridge system near  $73.5^{\circ}\text{N}$ . The acoustic signal from AR57 was lost as the float crossed the thermohaline front marking the boundary between the Greenland and Norwegian Seas. The warmer Norwegian Sea waters direct more of the acoustic energy to deeper depths. This probably caused a reduction in the surface duct trapping associated with the Polar waters, leading to blockage of the signal by the ridge system.

Simultaneously with the tracking of float AR50, float AR57 was detected some 150 km to the east and tracked during October and November 1989 heading northeast. Because this float was well removed from the Mohns Ridge, it

was apparent that the acoustic signals must have been diffracted over the ridge as well as passing through the numerous breaks in the ridge system.

A simulation of the Greenland Sea circulation by *Legutke* (1990) showed currents very similar to these float trajectories (Figure 27). Currents at the 341 m level of this wind-forced numerical model demonstrate quite similar features as those of the trajectory of MZ86. The flow out of the Boreas Basin is similar in magnitude to that of the observed float. This feeds an intensified boundary current along the slope and leads to the easterly circulation of the Jan Mayen Current closing the Greenland Sea Gyre. This model also shows the JMC flow turning to the north-northeast between  $0^{\circ}$  and  $3^{\circ}\text{E}$  as does MZ86. The north-northwest trajectories of MZ86 and AR50 are also well depicted although *Legutke* shows this to occur north of  $74^{\circ}\text{N}$ . She shows velocities along the Greenland slope on the order of  $20 \text{ cm s}^{-1}$  which compares well to the  $28 \text{ cm s}^{-1}$  observed here. Also a cross section through the model showed a similar slope-trapped boundary current.

A review of the velocity series in Figure 15 showed a possible periodic signal occurring at intervals of 3-7 days. A time series analysis of this data was done on the July data at the easterly end of MZ86, leg 3. This leg was analyzed because the initial time series showed evidence that a periodic signal may be present and the tracking was for more than 31 days. Figure 28 shows a plot of the energy density spectrum and indicates a peak in the spectra at a period of just over 3 days. This float is at 500 m during this leg and the bottom is smooth leading to the conclusion that this probably relates to energy from Kelvin waves propagating along the flow.

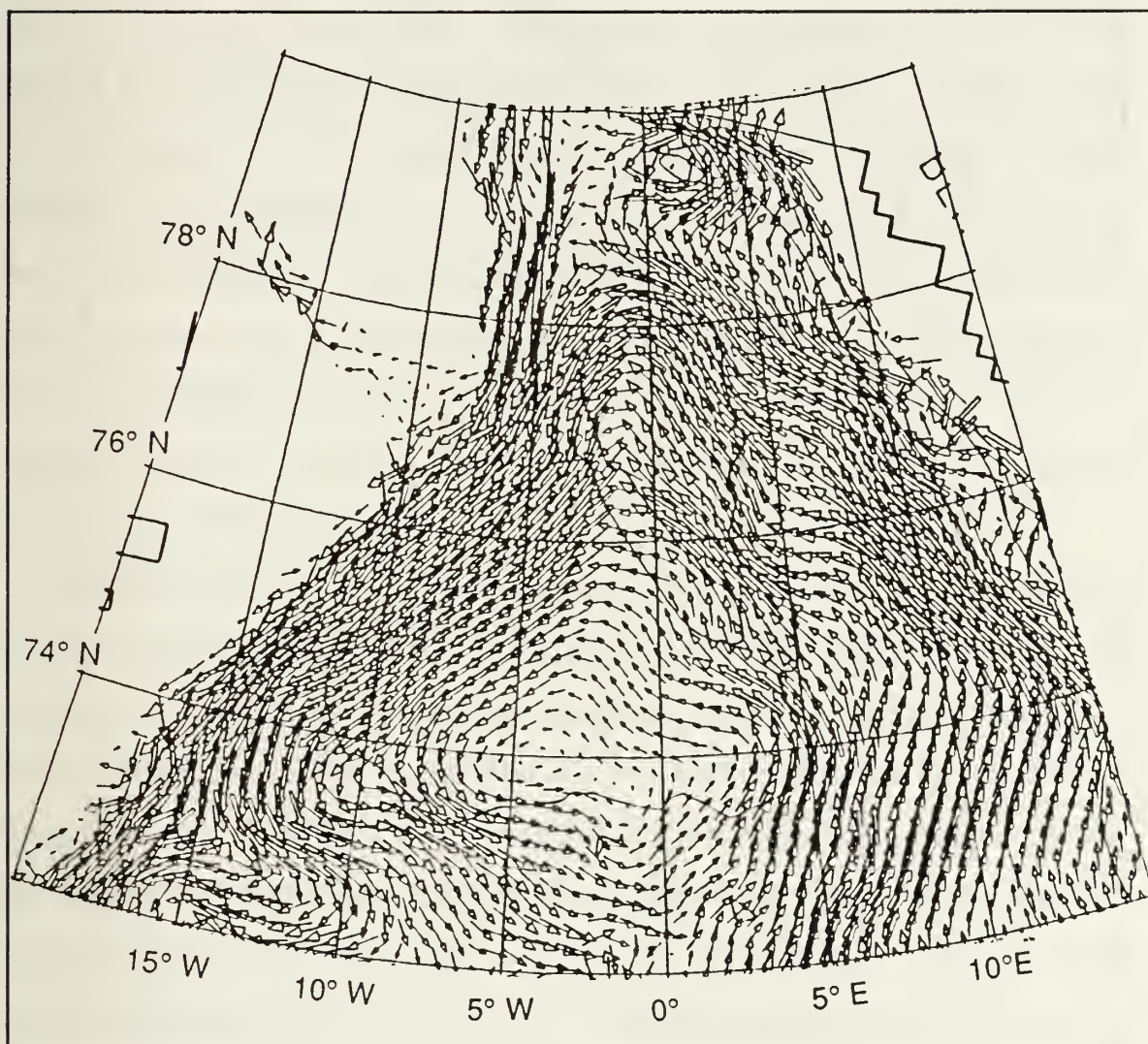


Figure 27. Current velocity at the 341 m level of the essentially barotropic and wind-forced model of *Legutke* (1990). Single line arrows represent speed  $< 3 \text{ cm s}^{-1}$  and hollow arrows represent speed  $> 3 \text{ cm s}^{-1}$ .

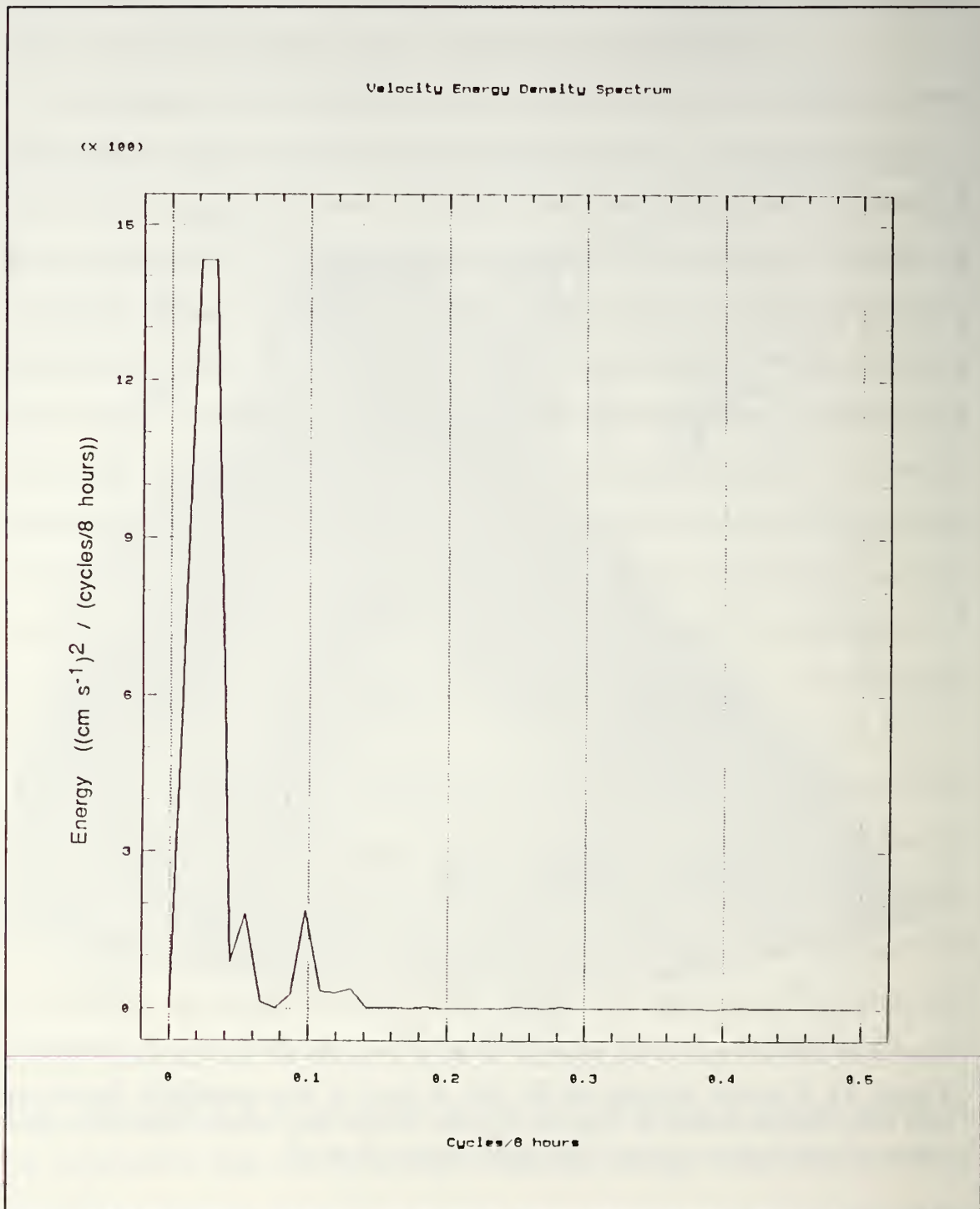


Figure 28 Energy density spectrum of the MZ86 velocity series from 3 July 1990 to 4 August 1990.

#### IV. CONCLUSIONS

A better understanding of the intermediate depth circulation in the Greenland Sea was the goal of this study. Trajectories of acoustically-tracked drifting SOFAR floats ballasted for depths ranging from 200 to 500 m were determined by processing the time of arrival data from a deployment of moored acoustic receivers in the Greenland Sea from September 1989 to August 1990. Sixteen floats were launched in Fram Strait during 1988 and 1989. Five of the sixteen floats launched were tracked during the 1989/90 deployment of the receivers. One float (MZ86) provided tracking information for ten months of the deployment period. The other floats provided tracking information ranging from several days to two months.

A strong flow ( $17 \text{ cm s}^{-1}$ ) was observed as MZ86 exited Fram Strait through the Boreas Basin and crossed the Greenland Fracture Zone (GFZ). The trajectory then moved parallel to the Greenland continental slope where the flow velocity at 350 m increased to  $28 \text{ cm s}^{-1}$ , characteristic of a bottom boundary current trapped along the slope. Near  $74^\circ\text{N}$  the float turned to the southeast as it approached the Jan Mayen Fracture Zone (JMFZ) and continued to the east to close the Greenland Sea Gyre. This portion of the flow is strongly barotropic with observed velocities at 500 m of  $3\text{-}5 \text{ cm s}^{-1}$ , similar to that recorded previously by a year-long current meter mooring intersected by the float. In the vicinity of  $3^\circ\text{E}$ , filaments of the Norwegian Atlantic Current (NAC) crossed through breaks in the Mohns Ridge and pushed the trajectory to the northwest, illustrating how the Jan Mayen Current merges with the NAC at intermediate depths .

Other features observed include bathymetric blocking of the signal especially as the float passed close to the Vesteris Seamount and also across Mohns Ridge. Because of the complexity of the Mohns Ridge topography, the signal was intermittently received at the listening arrays during its easterly drift. Meanders were observed as MZ86 drifted eastward in the Jan Mayen Current with a period of approximately three days, a wavelength of 40 km and an amplitude of 24 km. No indication of eddy energy was apparent during the transit along the Greenland slope nor when exiting the Boreas Basin.

## REFERENCES

- Aagaard, K., A synthesis of the Arctic Ocean circulation, *Rapp. P.-v. Réun. Cons. int. Explor. Mer.*, 188, 11-22, 1989.
- Aagaard, K., E. Fahrbach, J. Meinke, and J. H. Swift, Saline outflow from the Arctic Ocean: Its circulation to the deep waters of the Greenland, Norwegian, and Iceland Seas., *J. Geophys. Res.*, 96(C11), 20,433-20,441, 1991.
- Blythe, R. F., The Jan Mayen Current and the Deep Waters of the Greenland Basin, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1990.
- Bourke, R. H., J. L. Newton, R. G. Paquette, and M. D. Tunnicliffe, Circulation and water masses of the East Greenland Shelf, *J. Geophys. Res.*, 92(C7), 6741-6753, 1987.
- Bourke, R. H., A. M. Weigel, and R. G. Paquette, The westward turning branch of the West Spitsbergen Current, *J. Geophys. Res.*, 93(C11), 14,065-14,077, 1987.
- Bourke, R. H., R. G. Paquette, and R. F. Blythe, The Jan Mayen Current of the Greenland Sea, submitted to *J. Geophys. Res.*, 1991.
- Foldvik, A., K. Aagaard, T. Tørresen, On the velocity field of the East Greenland Current, *Deep Sea Res.*, 35(8), 1335-1354, 1988.
- Gascard, J. C., personal communication, December 1990.
- Gascard, J. C., C. Kergomard, P-F. Jeanin, M. Fily, Diagnostic study of the Fram Strait marginal ice zone during summer from 1983 and 1984 Marginal Ice Zone Experiment lagrangian observations, *J. Geophys. Res.*, 93(C4), 3613-3641, 1987.
- Gill, A. E., *Atmospheric Ocean Dynamics*, pp. 372, 389-391, Academic Press, 1982.
- GSP Group, MIZEX East 1987: Winter marginal ice program in the Fram Strait and Greenland Sea, *Eos Trans. Am. Geophys. Un.*, 70(17), 545-555, 1989.
- GSP Group, Greenland Sea Project, a venture toward improved understanding of the oceans role in climate, *Eos Trans. Am. Geophysic. Un.*, 71(24), 750-755, 1990.

- Hopkins, T. S., *The GIN Sea: Review of Physical Oceanography and Literature from 1972*, Undersea Research Centre Report SR-124, Viale San Bartolomeo 400 19026 San Bartolomeo (SP), Italy, July 1988.
- Johannessen, J.A., O. M. Johannessen, E. Svendsen, R. Shuchman, T. Manley, W. J. Campbell, E. G. Josberger, S. Sandven, J. C. Gascard, T. Olaussen, K. Davidson, and J. Van Leer, Mesoscale eddies in the Fram Strait marginal ice zone during the 1983 and 1984 marginal ice zone experiments, *J. Geophys. Res.*, 92(C7) 6754-6772, J., 1987.
- Koltermann, K. P. and H. Lüthje, *Hydrographic Atlas of the Greenland and Northern Norwegian Seas.*, p. 229, German Hydrographic Institute, Hamburg 1989.
- Legutke, S., A numerical investigation of the circulation in the Greenland and Norwegian Seas, *J. Phys. Oceanog.*, 21, 118-148, 1990.
- Manley, T.O. and K. L. Hunkins, Current regimes across the East Greenland Polar Front at 78°40' north latitude during summer 1984, *J. Geophys. Res.*, 92, no. C7, 6741-6753, 1987.
- Manley, T.O., J. C. Gascard, and W. B. Owens, The polar floats program, *IEEE J. Ocean. Eng.*, 14(2), 186-194, 1989.
- Morison, J., Seasonal variation in the West Spitsbergen Current estimated from bottom pressure measurements, *J. Geophys. Res.*, 96(C10), 18,381-18,395, 1991.
- Muench, R.D., G. S. E. Lagerloef, J. T. Gunn, 1984-85 current observations in the East Greenland Current: a preliminary description, *MIZEX Bulletin*, VII, Mar. 1986.
- Owens, W. P., The synoptic and statistical descriptions of the Gulf Stream and sub tropical gyre using SOFAR floats, *J. Phys. Oceanogr.*, 14, 104-113, 1984.
- Paquette, R. G., R. H. Bourke, J. L. Newton, and W. F. Perdue, The East Greenland Polar Front in autumn, *J. Geophys. Res.*, 90(C3), 1985.
- Quadfasel, D., J. C. Gascard, and K. P. Koltermann, Large-scale oceanography in Fram Strait during the 1984 marginal ice zone experiment, *J. Geophys. Res.*, 92(C7), 6719-6728, 1987.
- Rudels, B., Greenland Sea convection in the winter of 1987-1988, *J. Geophys. Res.*, 94(C3), 3223-3227, 1989.
- Smith, P. C., Baroclinic instability in the Denmark Strait overflow, *J. Phys. Oceanogr.*, 6, 355-371.

## APPENDIX A

### MZ86 POSITIONS

Positions of MZ86 from 27 September 1989 to 4 August 1990. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 10301802 | 78.235 | -8.225 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 927 302  | 77.573 | -0.517 |
| 9271102  | 77.515 | -0.459 |
| 9271902  | 77.464 | -0.512 |
| 928 302  | 77.417 | -0.400 |
| 9281102  | 77.372 | -0.290 |
| 9281902  | 77.329 | -0.190 |
| 929 302  | 77.286 | -0.109 |
| 9291102  | 77.247 | -0.059 |
| 9291902  | 77.216 | -0.050 |
| 930 302  | 77.190 | -0.081 |
| 9301102  | 77.164 | -0.133 |
| 9301902  | 77.138 | -0.197 |
| 10 1 302 | 77.111 | -0.265 |
| 10 11102 | 77.084 | -0.338 |
| 10 11902 | 77.058 | -0.426 |
| 10 2 302 | 77.032 | -0.562 |
| 10 21102 | 77.006 | -0.749 |
| 10 21902 | 76.978 | -0.948 |
| 10 3 302 | 76.951 | -1.152 |
| 10 31102 | 76.926 | -1.350 |
| 10 31902 | 76.911 | -1.519 |
| 10 4 302 | 76.906 | -1.651 |
| 10 41102 | 76.902 | -1.774 |
| 10 41902 | 76.898 | -1.894 |
| 10 5 302 | 76.890 | -2.033 |
| 10 51102 | 76.875 | -2.188 |
| 10 51902 | 76.858 | -2.342 |
| 10 6 302 | 76.840 | -2.491 |
| 10 61102 | 76.822 | -2.619 |
| 10 61902 | 76.799 | -2.740 |
| 10 7 302 | 76.770 | -2.861 |
| 10 71102 | 76.738 | -2.986 |
| 10 71902 | 76.704 | -3.124 |
| 10 8 302 | 76.669 | -3.263 |
| 10 81102 | 76.633 | -3.400 |
| 10 81902 | 76.597 | -3.529 |
| 10 9 302 | 76.560 | -3.659 |
| 10 91102 | 76.523 | -3.790 |
| 10 91902 | 76.490 | -3.927 |
| 1010 302 | 76.461 | -4.083 |
| 10101102 | 76.430 | -4.274 |
| 10101902 | 76.397 | -4.521 |
| 1011 302 | 76.357 | -4.809 |
| 10111102 | 76.307 | -5.115 |
| 10111902 | 76.248 | -5.427 |
| 1012 302 | 76.187 | -5.738 |
| 10121102 | 76.124 | -6.041 |
| 10121902 | 76.062 | -6.302 |
| 1013 302 | 76.004 | -6.536 |
| 10131102 | 75.954 | -6.765 |
| 10131902 | 75.909 | -6.998 |
| 1014 302 | 75.865 | -7.231 |
| 10141102 | 75.825 | -7.464 |
| 10141902 | 75.787 | -7.697 |
| 1015 302 | 75.751 | -7.932 |
| 10151102 | 75.716 | -8.161 |
| 10151902 | 75.682 | -8.380 |
| 1016 302 | 75.653 | -8.593 |
| 10161102 | 75.631 | -8.808 |
| 10161902 | 75.612 | -9.047 |

| MMDDHHMM | LAT    | LON     |
|----------|--------|---------|
| 1017 302 | 75.594 | -9.309  |
| 10171102 | 75.576 | -9.576  |
| 10171902 | 75.557 | -9.842  |
| 1018 302 | 75.534 | -10.104 |
| 10181102 | 75.504 | -10.366 |
| 10181902 | 75.461 | -10.621 |
| 1019 302 | 75.407 | -10.859 |
| 10191102 | 75.342 | -11.054 |
| 10191902 | 75.271 | -11.211 |
| 1020 302 | 75.195 | -11.349 |
| 10201102 | 75.117 | -11.480 |
| 10201902 | 75.037 | -11.611 |
| 1021 302 | 74.957 | -11.747 |
| 10211102 | 74.876 | -11.905 |
| 10211902 | 74.800 | -12.067 |
| 1022 302 | 74.729 | -12.225 |
| 10221102 | 74.660 | -12.379 |
| 10221902 | 74.590 | -12.527 |
| 1023 302 | 74.516 | -12.670 |
| 10231102 | 74.442 | -12.807 |
| 10231902 | 74.366 | -12.926 |
| 1024 302 | 74.293 | -13.004 |
| 10241102 | 74.225 | -13.032 |
| 10241902 | 74.164 | -13.027 |
| 1025 302 | 74.116 | -13.010 |
| 10251102 | 74.080 | -12.986 |
| 10251902 | 74.055 | -12.958 |
| 1026 302 | 74.038 | -12.936 |
| 10261102 | 74.025 | -12.916 |
| 10261902 | 74.015 | -12.897 |
| 1027 302 | 74.004 | -12.883 |
| 10271102 | 73.992 | -12.879 |
| 10271902 | 73.980 | -12.874 |
| 1028 302 | 73.967 | -12.861 |
| 10281102 | 73.948 | -12.844 |
| 10281902 | 73.923 | -12.822 |
| 1029 302 | 73.898 | -12.797 |
| 10291102 | 73.874 | -12.772 |
| 10291902 | 73.850 | -12.744 |
| 1030 302 | 73.829 | -12.711 |
| 10301102 | 73.812 | -12.682 |
| 10301902 | 73.794 | -12.660 |
| 1031 302 | 73.772 | -12.644 |
| 10311102 | 73.748 | -12.621 |
| 10311902 | 73.725 | -12.593 |
| 11 1 302 | 73.702 | -12.566 |
| 11 11102 | 73.680 | -12.542 |
| 11 11902 | 73.659 | -12.533 |
| 11 2 302 | 73.640 | -12.536 |
| 11 21102 | 73.626 | -12.539 |
| 11 21902 | 73.614 | -12.538 |
| 11 3 302 | 73.604 | -12.539 |
| 11 31102 | 73.594 | -12.541 |
| 11 31902 | 73.586 | -12.537 |
| 11 4 302 | 73.584 | -12.527 |
| 11 41102 | 73.585 | -12.516 |
| 11 41902 | 73.587 | -12.505 |
| 11 5 302 | 73.587 | -12.522 |
| 11 51102 | 73.579 | -12.571 |
| 11 51902 | 73.563 | -12.618 |

| MMDDHHMM | LAT    | LON     |
|----------|--------|---------|
| 11 6 302 | 73.545 | -12.653 |
| 11 61102 | 73.527 | -12.675 |
| 11 61902 | 73.510 | -12.692 |
| 11 7 302 | 73.497 | -12.711 |
| 11 71102 | 73.482 | -12.732 |
| 11 71902 | 73.464 | -12.750 |
| 11 8 302 | 73.440 | -12.741 |
| 11 81102 | 73.413 | -12.711 |
| 11 81902 | 73.394 | -12.684 |
| 11 9 302 | 73.396 | -12.676 |
| 11 91102 | 73.397 | -12.679 |
| 0 0 0    | 0.000  | 0.000   |
| 0 0 0    | 0.000  | 0.000   |
| 11131102 | 73.760 | -12.694 |
| 11131902 | 73.648 | -12.431 |
| 1114 302 | 73.692 | -12.443 |
| 11141102 | 73.691 | -12.455 |
| 11141902 | 73.690 | -12.467 |
| 1115 302 | 73.687 | -12.455 |
| 11151102 | 73.683 | -12.415 |
| 11151902 | 73.673 | -12.376 |
| 1116 302 | 73.661 | -12.336 |
| 11161102 | 73.647 | -12.300 |
| 11161902 | 73.633 | -12.264 |
| 1117 302 | 73.619 | -12.228 |
| 11171102 | 73.606 | -12.194 |
| 11171902 | 73.595 | -12.160 |
| 1118 302 | 73.584 | -12.124 |
| 11181102 | 73.574 | -12.080 |
| 11181902 | 73.561 | -12.029 |
| 1119 302 | 73.547 | -11.979 |
| 11191102 | 73.529 | -11.931 |
| 11191902 | 73.506 | -11.901 |
| 1120 302 | 73.479 | -11.886 |
| 11201102 | 73.450 | -11.871 |
| 11201902 | 73.420 | -11.852 |
| 1121 302 | 73.389 | -11.813 |
| 11211102 | 73.359 | -11.755 |
| 11211902 | 73.330 | -11.690 |
| 1122 302 | 73.304 | -11.624 |
| 11221102 | 73.280 | -11.559 |
| 11221902 | 73.262 | -11.506 |
| 1123 302 | 73.250 | -11.473 |
| 11231102 | 73.241 | -11.451 |
| 11231902 | 73.235 | -11.432 |
| 1124 302 | 73.229 | -11.410 |
| 11241102 | 73.224 | -11.381 |
| 11241902 | 73.219 | -11.335 |
| 1125 302 | 73.211 | -11.259 |
| 11251102 | 73.203 | -11.161 |
| 11251902 | 73.195 | -11.051 |
| 1126 302 | 73.187 | -10.925 |
| 11261102 | 73.172 | -10.747 |
| 11261902 | 73.167 | -10.629 |
| 0 0 0    | 0.000  | 0.000   |
| 0 0 0    | 0.000  | 0.000   |
| 1261902  | 72.177 | -9.434  |
| 127 302  | 72.390 | -9.717  |
| 1271102  | 72.591 | -9.906  |
| 1271902  | 72.658 | -9.903  |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 128 302  | 72.629 | -9.893 |
| 1281102  | 72.601 | -9.880 |
| 1281902  | 72.573 | -9.866 |
| 129 302  | 72.551 | -9.848 |
| 1291102  | 72.534 | -9.822 |
| 1291902  | 72.518 | -9.790 |
| 130 302  | 72.502 | -9.755 |
| 1301102  | 72.484 | -9.719 |
| 1301902  | 72.465 | -9.683 |
| 131 302  | 72.445 | -9.647 |
| 1311102  | 72.426 | -9.613 |
| 1311902  | 72.409 | -9.583 |
| 2 1 302  | 72.395 | -9.558 |
| 2 11102  | 72.389 | -9.543 |
| 2 11902  | 72.389 | -9.531 |
| 2 2 302  | 72.394 | -9.524 |
| 2 21102  | 72.400 | -9.518 |
| 2 21902  | 72.407 | -9.513 |
| 2 3 302  | 72.417 | -9.513 |
| 2 31102  | 72.388 | -9.461 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 213 302  | 72.594 | -8.563 |
| 2131102  | 72.683 | -8.547 |
| 2131902  | 72.763 | -8.512 |
| 214 302  | 72.772 | -8.421 |
| 2141102  | 72.736 | -8.330 |
| 2141902  | 72.701 | -8.239 |
| 215 302  | 72.667 | -8.170 |
| 2151102  | 72.636 | -8.132 |
| 2151902  | 72.604 | -8.091 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 2171102  | 72.537 | -7.224 |
| 2171902  | 72.512 | -7.151 |
| 218 302  | 72.505 | -7.084 |
| 2181102  | 72.509 | -7.021 |
| 2181902  | 72.517 | -6.958 |
| 219 302  | 72.528 | -6.900 |
| 2191102  | 72.542 | -6.851 |
| 2191902  | 72.558 | -6.802 |
| 220 302  | 72.573 | -6.754 |
| 2201102  | 72.586 | -6.697 |
| 2201902  | 72.595 | -6.628 |
| 221 302  | 72.603 | -6.557 |
| 2211102  | 72.611 | -6.487 |
| 2211902  | 72.622 | -6.426 |
| 222 302  | 72.641 | -6.375 |
| 2221102  | 72.664 | -6.330 |
| 2221902  | 72.689 | -6.287 |
| 223 302  | 72.714 | -6.242 |
| 2231102  | 72.737 | -6.186 |
| 2231902  | 72.754 | -6.119 |
| 224 302  | 72.768 | -6.051 |
| 2241102  | 72.782 | -5.985 |
| 2241902  | 72.797 | -5.924 |
| 225 302  | 72.814 | -5.872 |
| 2251102  | 72.837 | -5.833 |
| 2251902  | 72.869 | -5.810 |
| 226 302  | 72.906 | -5.804 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 2261102  | 72.947 | -5.809 |
| 2261902  | 72.990 | -5.823 |
| 227 302  | 73.035 | -5.849 |
| 2271102  | 73.084 | -5.887 |
| 2271902  | 73.136 | -5.935 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 328 302  | 73.023 | -5.222 |
| 3281102  | 72.979 | -4.946 |
| 3281902  | 72.983 | -4.898 |
| 329 302  | 72.975 | -4.867 |
| 3291102  | 72.968 | -4.836 |
| 3291902  | 72.961 | -4.807 |
| 330 302  | 72.955 | -4.780 |
| 3301102  | 72.949 | -4.753 |
| 3301902  | 72.942 | -4.723 |
| 331 302  | 72.935 | -4.691 |
| 3311102  | 72.929 | -4.660 |
| 3311902  | 72.927 | -4.632 |
| 4 1 302  | 72.926 | -4.614 |
| 4 11102  | 72.927 | -4.616 |
| 4 11902  | 72.931 | -4.644 |
| 4 2 302  | 72.937 | -4.687 |
| 4 21102  | 72.943 | -4.735 |
| 4 21902  | 72.949 | -4.780 |
| 4 3 302  | 72.953 | -4.819 |
| 4 31102  | 72.954 | -4.847 |
| 4 31902  | 72.948 | -4.845 |
| 4 4 302  | 72.936 | -4.813 |
| 4 41102  | 72.922 | -4.771 |
| 4 41902  | 72.906 | -4.725 |
| 4 5 302  | 72.890 | -4.681 |
| 4 51102  | 72.876 | -4.641 |
| 4 51902  | 72.862 | -4.605 |
| 4 6 302  | 72.850 | -4.570 |
| 4 61102  | 72.838 | -4.535 |
| 4 61902  | 72.826 | -4.485 |
| 4 7 302  | 72.817 | -4.423 |
| 4 71102  | 72.811 | -4.363 |
| 4 71902  | 72.809 | -4.309 |
| 4 8 302  | 72.814 | -4.269 |
| 4 81102  | 72.824 | -4.257 |
| 4 81902  | 72.838 | -4.279 |
| 4 9 302  | 72.854 | -4.316 |
| 4 91102  | 72.871 | -4.358 |
| 4 91902  | 72.888 | -4.401 |
| 410 302  | 72.903 | -4.441 |
| 4101102  | 72.916 | -4.463 |
| 4101902  | 72.924 | -4.457 |
| 411 302  | 72.926 | -4.427 |
| 4111102  | 72.925 | -4.391 |
| 4111902  | 72.921 | -4.353 |
| 412 302  | 72.915 | -4.319 |
| 4121102  | 72.908 | -4.301 |
| 4121902  | 72.902 | -4.308 |
| 413 302  | 72.901 | -4.331 |
| 4131102  | 72.903 | -4.359 |
| 4131902  | 72.905 | -4.388 |
| 414 302  | 72.908 | -4.416 |
| 4141102  | 72.909 | -4.437 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 4141902  | 72.910 | -4.456 |
| 415 302  | 72.909 | -4.472 |
| 4151102  | 72.907 | -4.483 |
| 4151902  | 72.903 | -4.488 |
| 416 302  | 72.900 | -4.490 |
| 4161102  | 72.898 | -4.491 |
| 4161902  | 72.896 | -4.491 |
| 417 302  | 72.893 | -4.484 |
| 4171102  | 72.887 | -4.465 |
| 4171902  | 72.875 | -4.436 |
| 418 302  | 72.863 | -4.402 |
| 4181102  | 72.849 | -4.367 |
| 4181902  | 72.956 | -4.409 |
| 419 302  | 72.852 | -4.311 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 4281902  | 73.195 | -4.698 |
| 429 302  | 73.182 | -4.522 |
| 4291102  | 73.140 | -4.316 |
| 4291902  | 73.104 | -4.122 |
| 430 302  | 73.070 | -3.938 |
| 4301102  | 73.039 | -3.769 |
| 4301902  | 73.013 | -3.620 |
| 5 1 302  | 72.991 | -3.501 |
| 5 11102  | 72.974 | -3.418 |
| 5 11902  | 72.968 | -3.371 |
| 5 2 302  | 72.970 | -3.351 |
| 5 21102  | 72.975 | -3.347 |
| 5 21902  | 72.981 | -3.352 |
| 5 3 302  | 72.988 | -3.362 |
| 5 31102  | 72.995 | -3.373 |
| 5 31902  | 73.002 | -3.385 |
| 5 4 302  | 73.011 | -3.399 |
| 5 41102  | 73.020 | -3.412 |
| 5 41902  | 73.029 | -3.415 |
| 5 5 302  | 73.032 | -3.400 |
| 5 51102  | 73.028 | -3.382 |
| 5 51902  | 73.020 | -3.369 |
| 5 6 302  | 73.011 | -3.361 |
| 5 61102  | 73.003 | -3.357 |
| 5 61902  | 73.000 | -3.348 |
| 5 7 302  | 73.003 | -3.336 |
| 5 71102  | 73.007 | -3.323 |
| 5 71902  | 73.010 | -3.314 |
| 5 8 302  | 73.011 | -3.306 |
| 5 81102  | 73.012 | -3.297 |
| 5 81902  | 73.013 | -3.290 |
| 5 9 302  | 73.014 | -3.285 |
| 5 91102  | 73.016 | -3.280 |
| 5 91902  | 73.021 | -3.279 |
| 510 302  | 73.031 | -3.284 |
| 5101102  | 73.041 | -3.293 |
| 5101902  | 73.050 | -3.297 |
| 511 302  | 73.056 | -3.286 |
| 5111102  | 73.061 | -3.257 |
| 5111902  | 73.066 | -3.225 |
| 512 302  | 73.071 | -3.193 |
| 5121102  | 73.081 | -3.204 |
| 5121902  | 73.097 | -3.263 |
| 513 302  | 73.115 | -3.323 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 5131102  | 73.134 | -3.380 |
| 5131902  | 73.154 | -3.414 |
| 514 302  | 73.175 | -3.431 |
| 5141102  | 73.196 | -3.447 |
| 5141902  | 73.216 | -3.463 |
| 515 302  | 73.229 | -3.473 |
| 5151102  | 73.235 | -3.457 |
| 5151902  | 73.239 | -3.410 |
| 516 302  | 73.242 | -3.348 |
| 5161102  | 73.245 | -3.283 |
| 5161902  | 73.247 | -3.211 |
| 517 302  | 73.244 | -3.124 |
| 5171102  | 73.233 | -3.012 |
| 5171902  | 73.218 | -2.885 |
| 518 302  | 73.202 | -2.750 |
| 5181102  | 73.187 | -2.615 |
| 5181902  | 73.173 | -2.482 |
| 519 302  | 73.158 | -2.379 |
| 5191102  | 73.141 | -2.298 |
| 5191902  | 73.125 | -2.217 |
| 520 302  | 73.110 | -2.137 |
| 5201102  | 73.100 | -2.075 |
| 5201902  | 73.090 | -2.032 |
| 521 302  | 73.080 | -1.992 |
| 5211102  | 73.070 | -1.947 |
| 5211902  | 73.060 | -1.894 |
| 522 302  | 73.050 | -1.841 |
| 5221102  | 73.045 | -1.788 |
| 5221902  | 73.044 | -1.755 |
| 523 302  | 73.044 | -1.742 |
| 5231102  | 73.044 | -1.731 |
| 5231902  | 73.048 | -1.725 |
| 524 302  | 73.056 | -1.720 |
| 5241102  | 73.065 | -1.708 |
| 5241902  | 73.073 | -1.679 |
| 525 302  | 73.077 | -1.644 |
| 5251102  | 73.078 | -1.607 |
| 5251902  | 73.078 | -1.566 |
| 526 302  | 73.076 | -1.525 |
| 5261102  | 73.070 | -1.495 |
| 5261902  | 73.063 | -1.482 |
| 527 302  | 73.056 | -1.472 |
| 5271102  | 73.051 | -1.461 |
| 5271902  | 73.047 | -1.453 |
| 528 302  | 73.041 | -1.454 |
| 5281102  | 73.032 | -1.456 |
| 5281902  | 73.023 | -1.461 |
| 529 302  | 73.015 | -1.473 |
| 5291102  | 73.009 | -1.495 |
| 5291902  | 73.005 | -1.525 |
| 530 302  | 73.001 | -1.557 |
| 5301102  | 72.997 | -1.587 |
| 5301902  | 72.995 | -1.616 |
| 531 302  | 72.998 | -1.645 |
| 5311102  | 73.000 | -1.666 |
| 5311902  | 73.002 | -1.674 |
| 6 1 302  | 73.003 | -1.669 |
| 6 11102  | 73.003 | -1.652 |
| 6 11902  | 73.002 | -1.632 |
| 6 2 302  | 72.998 | -1.609 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 6 21102  | 72.993 | -1.590 |
| 6 21902  | 72.987 | -1.580 |
| 6 3 302  | 72.980 | -1.584 |
| 6 31102  | 72.973 | -1.599 |
| 6 31902  | 72.967 | -1.616 |
| 6 4 302  | 72.961 | -1.633 |
| 6 41102  | 72.955 | -1.648 |
| 6 41902  | 72.945 | -1.621 |
| 6 5 302  | 72.928 | -1.556 |
| 6 51102  | 72.907 | -1.490 |
| 6 51902  | 72.885 | -1.428 |
| 6 6 302  | 72.865 | -1.378 |
| 6 61102  | 72.847 | -1.353 |
| 6 61902  | 72.830 | -1.353 |
| 6 7 302  | 72.813 | -1.362 |
| 6 71102  | 72.800 | -1.375 |
| 6 71902  | 72.790 | -1.392 |
| 6 8 302  | 72.781 | -1.410 |
| 6 81102  | 72.771 | -1.429 |
| 6 81902  | 72.762 | -1.444 |
| 6 9 302  | 72.754 | -1.454 |
| 6 91102  | 72.749 | -1.459 |
| 6 91902  | 72.745 | -1.460 |
| 610 302  | 72.741 | -1.461 |
| 6101102  | 72.737 | -1.461 |
| 6101902  | 72.735 | -1.459 |
| 611 302  | 72.735 | -1.457 |
| 6111102  | 72.737 | -1.457 |
| 6111902  | 72.739 | -1.457 |
| 612 302  | 72.740 | -1.460 |
| 6121102  | 72.741 | -1.470 |
| 6121902  | 72.742 | -1.487 |
| 613 302  | 72.743 | -1.508 |
| 6131102  | 72.745 | -1.529 |
| 6131902  | 72.748 | -1.552 |
| 614 302  | 72.751 | -1.578 |
| 6141102  | 72.753 | -1.604 |
| 6141902  | 72.755 | -1.630 |
| 615 302  | 72.756 | -1.643 |
| 6151102  | 72.757 | -1.643 |
| 6151902  | 72.758 | -1.643 |
| 616 302  | 72.758 | -1.644 |
| 6161102  | 72.756 | -1.647 |
| 6161902  | 72.751 | -1.650 |
| 617 302  | 72.744 | -1.651 |
| 6171102  | 72.732 | -1.646 |
| 6171902  | 72.717 | -1.636 |
| 618 302  | 72.701 | -1.619 |
| 6181102  | 72.685 | -1.597 |
| 6181902  | 72.672 | -1.572 |
| 619 302  | 72.665 | -1.546 |
| 6191102  | 72.662 | -1.538 |
| 6191902  | 72.658 | -1.548 |
| 620 302  | 72.651 | -1.559 |
| 6201102  | 72.639 | -1.570 |
| 6201902  | 72.626 | -1.581 |
| 621 302  | 72.614 | -1.593 |
| 6211102  | 72.606 | -1.603 |
| 6211902  | 72.601 | -1.612 |
| 622 302  | 72.597 | -1.628 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 6221102  | 72.593 | -1.667 |
| 6221902  | 72.588 | -1.733 |
| 623 302  | 72.574 | -1.812 |
| 6231102  | 72.555 | -1.893 |
| 6231902  | 72.536 | -1.971 |
| 624 302  | 72.518 | -2.034 |
| 6241102  | 72.502 | -2.071 |
| 6241902  | 72.487 | -2.087 |
| 625 302  | 72.471 | -2.098 |
| 6251102  | 72.455 | -2.108 |
| 6251902  | 72.440 | -2.119 |
| 626 302  | 72.425 | -2.129 |
| 6261102  | 72.410 | -2.140 |
| 6261902  | 72.394 | -2.150 |
| 627 302  | 72.374 | -2.161 |
| 6271102  | 72.352 | -2.162 |
| 6271902  | 72.329 | -2.150 |
| 628 302  | 72.306 | -2.137 |
| 6281102  | 72.289 | -2.125 |
| 6281902  | 72.278 | -2.067 |
| 629 302  | 72.267 | -1.941 |
| 6291102  | 72.259 | -1.809 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 7 31102  | 72.013 | -0.542 |
| 7 31902  | 72.022 | -0.372 |
| 7 4 302  | 72.032 | -0.163 |
| 7 41102  | 72.034 | -0.092 |
| 7 41902  | 72.026 | -0.071 |
| 7 5 302  | 72.015 | -0.051 |
| 7 51102  | 72.002 | -0.026 |
| 7 51902  | 71.991 | 0.009  |
| 7 6 302  | 71.983 | 0.066  |
| 7 61102  | 71.983 | 0.159  |
| 7 61902  | 71.997 | 0.298  |
| 7 7 302  | 72.022 | 0.461  |
| 7 71102  | 72.051 | 0.636  |
| 7 71902  | 72.084 | 0.815  |
| 7 8 302  | 72.117 | 0.993  |
| 7 81102  | 72.148 | 1.168  |
| 7 81902  | 72.173 | 1.344  |
| 7 9 302  | 72.189 | 1.530  |
| 7 91102  | 72.204 | 1.727  |
| 7 91902  | 72.218 | 1.926  |
| 710 302  | 72.233 | 2.120  |
| 7101102  | 72.248 | 2.306  |
| 7101902  | 72.264 | 2.469  |
| 711 302  | 72.279 | 2.590  |
| 7111102  | 72.292 | 2.676  |
| 7111902  | 72.301 | 2.745  |
| 712 302  | 72.306 | 2.806  |
| 7121102  | 72.309 | 2.864  |
| 7121902  | 72.313 | 2.920  |
| 713 302  | 72.317 | 2.963  |
| 7131102  | 72.323 | 2.991  |
| 7131902  | 72.329 | 3.009  |
| 714 302  | 72.335 | 3.016  |
| 7141102  | 72.338 | 3.017  |
| 7141902  | 72.340 | 3.015  |
| 715 302  | 72.344 | 3.017  |

| MMDDHHMM | LAT    | LON   |
|----------|--------|-------|
| 7151102  | 72.349 | 3.022 |
| 7151902  | 72.355 | 3.031 |
| 716 302  | 72.361 | 3.043 |
| 7161102  | 72.367 | 3.061 |
| 7161902  | 72.371 | 3.081 |
| 717 302  | 72.375 | 3.098 |
| 7171102  | 72.382 | 3.114 |
| 7171902  | 72.395 | 3.150 |
| 718 302  | 72.408 | 3.212 |
| 7181102  | 72.419 | 3.278 |
| 7181902  | 72.428 | 3.348 |
| 719 302  | 72.436 | 3.413 |
| 7191102  | 72.446 | 3.473 |
| 7191902  | 72.467 | 3.520 |
| 720 302  | 72.498 | 3.543 |
| 7201102  | 72.528 | 3.527 |
| 7201902  | 72.558 | 3.487 |
| 721 302  | 72.585 | 3.436 |
| 7211102  | 72.602 | 3.381 |
| 7211902  | 72.607 | 3.329 |
| 722 302  | 72.607 | 3.293 |
| 7221102  | 72.604 | 3.285 |
| 7221902  | 72.602 | 3.294 |
| 723 302  | 72.602 | 3.306 |
| 7231102  | 72.606 | 3.314 |
| 7231902  | 72.615 | 3.317 |
| 724 302  | 72.626 | 3.296 |
| 7241102  | 72.638 | 3.249 |
| 7241902  | 72.650 | 3.193 |
| 725 302  | 72.662 | 3.135 |
| 7251102  | 72.677 | 3.095 |
| 7251902  | 72.691 | 3.072 |
| 726 302  | 72.705 | 3.049 |
| 7261102  | 72.719 | 3.024 |
| 7261902  | 72.733 | 2.967 |
| 727 302  | 72.745 | 2.878 |
| 7271102  | 72.753 | 2.788 |
| 7271902  | 72.762 | 2.697 |
| 728 302  | 72.771 | 2.604 |
| 7281102  | 72.780 | 2.516 |
| 7281902  | 72.785 | 2.467 |
| 729 302  | 72.788 | 2.455 |
| 7291102  | 72.791 | 2.443 |
| 7291902  | 72.794 | 2.431 |
| 730 302  | 72.802 | 2.417 |
| 7301102  | 72.816 | 2.382 |
| 7301902  | 72.831 | 2.333 |
| 731 302  | 72.846 | 2.284 |
| 7311102  | 72.861 | 2.248 |
| 7311902  | 72.875 | 2.233 |
| 8 1 302  | 72.885 | 2.220 |
| 8 11102  | 72.891 | 2.205 |
| 8 11902  | 72.894 | 2.191 |
| 8 2 302  | 72.894 | 2.180 |
| 8 21102  | 72.893 | 2.168 |
| 8 21902  | 72.892 | 2.151 |
| 8 3 302  | 72.891 | 2.132 |
| 8 31102  | 72.889 | 2.113 |
| 8 31902  | 72.890 | 2.092 |
| 8 4 302  | 72.883 | 2.087 |

## APPENDIX B

### AR50 POSITIONS

Positions of AR50 from 24 September 1989 to 25 November 1989. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 10301802 | 78.235 | -8.225 |

| MMDDHHMM | LAT    | LON   | MMDDHHMM | LAT    | LON   |
|----------|--------|-------|----------|--------|-------|
| 924 901  | 72.244 | 4.819 | 1014 901 | 73.524 | 2.557 |
| 9241701  | 72.268 | 4.703 | 10141701 | 73.546 | 2.543 |
| 925 101  | 72.292 | 4.614 | 1015 101 | 73.568 | 2.551 |
| 925 901  | 72.318 | 4.565 | 1015 901 | 73.591 | 2.569 |
| 9251701  | 72.345 | 4.518 | 10151701 | 73.613 | 2.590 |
| 926 101  | 72.373 | 4.462 | 1016 101 | 73.635 | 2.610 |
| 926 901  | 72.400 | 4.396 | 1016 901 | 73.655 | 2.627 |
| 9261701  | 72.424 | 4.330 | 10161701 | 73.673 | 2.644 |
| 927 101  | 72.449 | 4.263 | 1017 101 | 73.688 | 2.665 |
| 927 901  | 72.472 | 4.206 | 1017 901 | 73.702 | 2.694 |
| 9271701  | 72.497 | 4.169 | 10171701 | 73.714 | 2.725 |
| 928 101  | 72.521 | 4.138 | 1018 101 | 73.727 | 2.756 |
| 928 901  | 72.546 | 4.107 | 1018 901 | 73.740 | 2.787 |
| 9281701  | 72.568 | 4.074 | 10181701 | 73.753 | 2.820 |
| 929 101  | 72.587 | 4.033 | 1019 101 | 73.768 | 2.863 |
| 929 901  | 72.607 | 3.991 | 1019 901 | 73.784 | 2.909 |
| 9291701  | 72.626 | 3.949 | 10191701 | 73.799 | 2.954 |
| 930 101  | 72.647 | 3.905 | 1020 101 | 73.815 | 2.992 |
| 930 901  | 72.668 | 3.847 | 1020 901 | 73.828 | 3.009 |
| 9301701  | 72.690 | 3.775 | 10201701 | 73.840 | 3.009 |
| 10 1 101 | 72.710 | 3.703 | 1021 101 | 73.850 | 3.004 |
| 10 1 901 | 72.730 | 3.637 | 1021 901 | 73.860 | 2.997 |
| 10 11701 | 72.749 | 3.578 | 10211701 | 73.870 | 2.998 |
| 10 2 101 | 72.769 | 3.520 | 1022 101 | 73.878 | 3.005 |
| 10 2 901 | 72.791 | 3.462 | 1022 901 | 73.885 | 3.012 |
| 10 21701 | 72.813 | 3.405 | 10221701 | 73.892 | 3.021 |
| 10 3 101 | 72.834 | 3.350 | 1023 101 | 73.899 | 3.030 |
| 10 3 901 | 72.855 | 3.295 | 1023 901 | 73.906 | 3.039 |
| 10 31701 | 72.876 | 3.239 | 10231701 | 73.911 | 3.036 |
| 10 4 101 | 72.897 | 3.185 | 1024 101 | 73.916 | 3.020 |
| 10 4 901 | 72.918 | 3.131 | 1024 901 | 73.920 | 3.005 |
| 10 41701 | 72.939 | 3.082 | 10241701 | 73.925 | 2.994 |
| 10 5 101 | 72.960 | 3.039 | 1025 101 | 73.930 | 2.985 |
| 10 5 901 | 72.980 | 2.995 | 1025 901 | 73.935 | 2.977 |
| 10 51701 | 73.001 | 2.953 | 10251701 | 73.941 | 2.962 |
| 10 6 101 | 73.021 | 2.912 | 1026 101 | 73.944 | 2.936 |
| 10 6 901 | 73.041 | 2.874 | 1026 901 | 73.945 | 2.911 |
| 10 61701 | 73.061 | 2.840 | 10261701 | 73.946 | 2.886 |
| 10 7 101 | 73.079 | 2.807 | 1027 101 | 73.946 | 2.866 |
| 10 7 901 | 73.097 | 2.776 | 1027 901 | 73.948 | 2.862 |
| 10 71701 | 73.114 | 2.746 | 10271701 | 73.951 | 2.879 |
| 10 8 101 | 73.132 | 2.719 | 1028 101 | 73.955 | 2.912 |
| 10 8 901 | 73.152 | 2.697 | 1028 901 | 73.959 | 2.951 |
| 10 81701 | 73.174 | 2.679 | 10281701 | 73.963 | 2.991 |
| 10 9 101 | 73.196 | 2.660 | 1029 101 | 73.966 | 3.028 |
| 10 9 901 | 73.218 | 2.643 | 1029 901 | 73.969 | 3.064 |
| 10 91701 | 73.240 | 2.637 | 10291701 | 73.977 | 3.061 |
| 1010 101 | 73.261 | 2.650 | 1030 101 | 74.031 | 2.576 |
| 1010 901 | 73.281 | 2.675 | 0 0 0    | 0.000  | 0.000 |
| 10101701 | 73.302 | 2.703 | 0 0 0    | 0.000  | 0.000 |
| 1011 101 | 73.321 | 2.730 | 11 2 901 | 74.009 | 3.256 |
| 1011 901 | 73.340 | 2.754 | 11 21701 | 74.019 | 3.269 |
| 10111701 | 73.358 | 2.769 | 11 3 101 | 74.021 | 3.282 |
| 1012 101 | 73.376 | 2.766 | 11 3 901 | 74.015 | 3.284 |
| 1012 901 | 73.396 | 2.753 | 11 31701 | 74.010 | 3.279 |
| 10121701 | 73.418 | 2.734 | 11 4 101 | 74.004 | 3.276 |
| 1013 101 | 73.440 | 2.705 | 11 4 901 | 74.000 | 3.275 |
| 1013 901 | 73.462 | 2.668 | 11 41701 | 73.996 | 3.282 |
| 10131701 | 73.483 | 2.629 | 11 5 101 | 73.992 | 3.299 |
| 1014 101 | 73.504 | 2.592 | 11 5 901 | 73.988 | 3.320 |

| MMDDHHMM | LAT    | LON   |
|----------|--------|-------|
| 11 51701 | 73.984 | 3.342 |
| 11 6 101 | 73.979 | 3.364 |
| 11 6 901 | 73.973 | 3.387 |
| 11 61701 | 73.967 | 3.414 |
| 11 7 101 | 73.960 | 3.452 |
| 11 7 901 | 73.953 | 3.499 |
| 11 71701 | 73.946 | 3.549 |
| 11 8 101 | 73.939 | 3.601 |
| 11 8 901 | 73.932 | 3.652 |
| 11 81701 | 73.924 | 3.703 |
| 11 9 101 | 73.916 | 3.753 |
| 11 9 901 | 73.907 | 3.804 |
| 11 91701 | 73.897 | 3.859 |
| 1110 101 | 73.887 | 3.916 |
| 1110 901 | 73.875 | 3.973 |
| 11101701 | 73.863 | 4.028 |
| 1111 101 | 73.850 | 4.082 |
| 1111 901 | 73.838 | 4.136 |
| 11111701 | 73.826 | 4.190 |
| 1112 101 | 73.813 | 4.249 |
| 1112 901 | 73.801 | 4.316 |
| 11121701 | 73.789 | 4.383 |
| 1113 101 | 73.777 | 4.450 |
| 1113 901 | 73.766 | 4.513 |
| 11131701 | 73.755 | 4.539 |
| 1114 101 | 73.743 | 4.582 |
| 0 0 0    | 0.000  | 0.000 |
| 0 0 0    | 0.000  | 0.000 |
| 1118 101 | 73.635 | 5.569 |
| 1118 901 | 73.627 | 5.685 |
| 11181701 | 73.625 | 5.802 |
| 1119 101 | 73.627 | 5.931 |
| 1119 901 | 73.629 | 6.061 |
| 11191701 | 73.631 | 6.190 |
| 1120 101 | 73.632 | 6.312 |
| 1120 901 | 73.630 | 6.425 |
| 11201701 | 73.625 | 6.522 |
| 1121 101 | 73.617 | 6.599 |
| 1121 901 | 73.605 | 6.665 |
| 11211701 | 73.591 | 6.724 |
| 1122 101 | 73.576 | 6.779 |
| 1122 901 | 73.561 | 6.832 |
| 11221701 | 73.545 | 6.885 |
| 1123 101 | 73.530 | 6.943 |
| 1123 901 | 73.518 | 7.013 |
| 11231701 | 73.510 | 7.096 |
| 1124 101 | 73.502 | 7.185 |
| 1124 901 | 73.494 | 7.275 |
| 11241701 | 73.483 | 7.369 |
| 1125 101 | 73.473 | 7.463 |

## APPENDIX C

### AR57 POSITIONS

Positions of AR57 from 22 September 1989 to 19 November 1989 . Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 10301802 | 78.235 | -8.225 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 9221011  | 72.341 | 11.858 |
| 923 211  | 72.393 | 12.045 |
| 9231811  | 72.410 | 12.128 |
| 924 211  | 72.421 | 12.175 |
| 9241011  | 72.433 | 12.224 |
| 9241811  | 72.444 | 12.273 |
| 925 211  | 72.456 | 12.322 |
| 9251011  | 72.464 | 12.371 |
| 9251811  | 72.469 | 12.418 |
| 926 211  | 72.474 | 12.463 |
| 9261011  | 72.479 | 12.505 |
| 9261811  | 72.484 | 12.545 |
| 927 211  | 72.488 | 12.585 |
| 9271011  | 72.492 | 12.625 |
| 9271811  | 72.497 | 12.667 |
| 928 211  | 72.503 | 12.712 |
| 9281011  | 72.511 | 12.764 |
| 9281811  | 72.523 | 12.823 |
| 929 211  | 72.537 | 12.885 |
| 9291011  | 72.552 | 12.949 |
| 9291811  | 72.566 | 13.013 |
| 930 211  | 72.580 | 13.077 |
| 9301011  | 72.593 | 13.138 |
| 9301811  | 72.604 | 13.195 |
| 10 1 211 | 72.612 | 13.246 |
| 10 11011 | 72.617 | 13.293 |
| 10 11811 | 72.618 | 13.332 |
| 10 2 211 | 72.616 | 13.362 |
| 10 21011 | 72.611 | 13.382 |
| 10 21811 | 72.603 | 13.396 |
| 10 3 211 | 72.593 | 13.409 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 10111811 | 72.164 | 13.526 |
| 1012 211 | 71.988 | 12.909 |
| 10121011 | 72.038 | 13.102 |
| 10121811 | 72.030 | 13.106 |
| 1013 211 | 72.022 | 13.111 |
| 10131011 | 72.015 | 13.117 |
| 10131811 | 72.008 | 13.121 |
| 1014 211 | 72.001 | 13.125 |
| 10141011 | 71.995 | 13.124 |
| 10141811 | 71.988 | 13.117 |
| 1015 211 | 71.982 | 13.107 |
| 10151011 | 71.977 | 13.094 |
| 10151811 | 71.972 | 13.080 |
| 1016 211 | 71.967 | 13.063 |
| 10161011 | 71.961 | 13.044 |
| 10161811 | 71.954 | 13.018 |
| 1017 211 | 71.946 | 12.984 |
| 10181011 | 71.935 | 12.944 |
| 10181811 | 71.924 | 12.901 |
| 1019 211 | 71.912 | 12.856 |
| 10191011 | 71.900 | 12.810 |
| 10191811 | 71.887 | 12.762 |
| 1020 211 | 71.886 | 12.781 |
| 10231011 | 71.941 | 13.174 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 10291811 | 72.473 | 15.305 |

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 1030 211 | 72.493 | 15.382 |
| 10301011 | 72.504 | 15.452 |
| 10301811 | 72.511 | 15.507 |
| 1031 211 | 72.517 | 15.546 |
| 10311011 | 72.521 | 15.577 |
| 10311811 | 72.521 | 15.602 |
| 11 1 211 | 72.518 | 15.624 |
| 11 11011 | 72.514 | 15.641 |
| 11 11811 | 72.509 | 15.658 |
| 11 2 211 | 72.505 | 15.676 |
| 11 21011 | 72.519 | 15.730 |
| 11 21811 | 72.540 | 15.790 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 11 61811 | 72.653 | 16.349 |
| 11 7 211 | 72.642 | 16.362 |
| 11 71011 | 72.639 | 16.382 |
| 11 71811 | 72.631 | 16.393 |
| 11 8 211 | 72.622 | 16.404 |
| 11 81011 | 72.614 | 16.414 |
| 11 81811 | 72.605 | 16.424 |
| 11 9 211 | 72.596 | 16.434 |
| 11 91011 | 72.586 | 16.442 |
| 11 91811 | 72.574 | 16.450 |
| 1110 211 | 72.562 | 16.457 |
| 11101011 | 72.550 | 16.464 |
| 11101811 | 72.537 | 16.470 |
| 1111 211 | 72.524 | 16.475 |
| 11111011 | 72.508 | 16.475 |
| 11111811 | 72.489 | 16.477 |
| 0 0 0    | 0.000  | 0.000  |
| 0 0 0    | 0.000  | 0.000  |
| 11151811 | 72.600 | 17.017 |
| 1116 211 | 72.592 | 17.047 |
| 11161011 | 72.574 | 17.056 |
| 11161811 | 72.559 | 17.065 |
| 1117 211 | 72.544 | 17.074 |
| 11171011 | 72.528 | 17.082 |
| 11171811 | 72.512 | 17.089 |
| 1118 211 | 72.495 | 17.095 |
| 11181011 | 72.477 | 17.101 |
| 11181811 | 72.459 | 17.106 |
| 1119 211 | 72.441 | 17.112 |
| 11191011 | 72.454 | 17.135 |
| 11191811 | 72.456 | 17.164 |

## APPENDIX D

### AR48 POSITIONS

Positions of AR48 from 26 October 1989 to 1 November 1989. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 10301802 | 78.235 | -8.225 |

| MMDDHHMM |     | LAT    | LON    |
|----------|-----|--------|--------|
| 1026     | 41  | 72.889 | -6.201 |
| 1026     | 841 | 72.900 | -6.218 |
| 10261641 |     | 72.902 | -6.216 |
| 1027     | 41  | 72.907 | -6.228 |
| 1027     | 841 | 72.906 | -6.221 |
| 10271641 |     | 72.909 | -6.224 |
| 1028     | 41  | 72.912 | -6.232 |
| 1028     | 841 | 72.917 | -6.243 |
| 10281641 |     | 72.920 | -6.254 |
| 1029     | 41  | 72.841 | -6.254 |
| 1029     | 841 | 72.849 | -6.277 |
| 10291641 |     | 72.854 | -6.303 |
| 1030     | 41  | 72.849 | -6.314 |
| 1030     | 841 | 72.845 | -6.334 |
| 10301641 |     | 72.844 | -6.354 |
| 1031     | 41  | 72.833 | -6.350 |
| 1031     | 841 | 72.834 | -6.384 |
| 10311641 |     | 72.834 | -6.418 |
| 11       | 1   | 41     | 72.832 |
| 11       | 1   | 841    | 72.829 |
| 11       | 1   | 841    | 72.829 |
| 11       | 1   | 841    | 72.829 |

## APPENDIX E

### MZ83 POSITIONS

Positions of MZ83 from 9 MAY 1990 to 28 JUNE 1990. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

| MMDDHHMM | LAT    | LON    |
|----------|--------|--------|
| 10301802 | 78.235 | -8.225 |

| MMDDHHMM | LAT    | LON     |
|----------|--------|---------|
| 5 91032  | 73.258 | -11.498 |
| 5 91832  | 73.281 | -11.424 |
| 510 232  | 73.304 | -11.341 |
| 5101032  | 73.319 | -11.331 |
| 5101832  | 73.321 | -11.326 |
| 511 232  | 73.317 | -11.321 |
| 5111032  | 73.312 | -11.308 |
| 5111832  | 73.307 | -11.282 |
| 512 232  | 73.306 | -11.237 |
| 5121032  | 73.310 | -11.190 |
| 5121832  | 73.313 | -11.142 |
| 513 232  | 73.317 | -11.094 |
| 5131032  | 73.325 | -11.048 |
| 5131832  | 73.338 | -10.998 |
| 514 232  | 73.355 | -10.947 |
| 5141032  | 73.373 | -10.898 |
| 5141832  | 73.392 | -10.860 |
| 515 232  | 73.411 | -10.833 |
| 5151032  | 73.429 | -10.805 |
| 5151832  | 73.447 | -10.779 |
| 516 232  | 73.464 | -10.758 |
| 5161032  | 73.478 | -10.733 |
| 5161832  | 73.483 | -10.711 |
| 517 232  | 73.483 | -10.699 |
| 5171032  | 73.482 | -10.695 |
| 5171832  | 73.481 | -10.683 |
| 518 232  | 73.481 | -10.655 |
| 5181032  | 73.484 | -10.611 |
| 5181832  | 73.493 | -10.566 |
| 519 232  | 73.510 | -10.521 |
| 5191032  | 73.531 | -10.477 |
| 5191832  | 73.554 | -10.443 |
| 520 232  | 73.579 | -10.427 |
| 5201032  | 73.602 | -10.418 |
| 5201832  | 73.623 | -10.402 |
| 521 232  | 73.635 | -10.370 |
| 5211032  | 73.637 | -10.303 |
| 5211832  | 73.630 | -10.174 |
| 522 232  | 73.620 | -10.008 |
| 5221032  | 73.609 | -9.825  |
| 5221832  | 73.599 | -9.638  |
| 523 232  | 73.596 | -9.457  |
| 5231032  | 73.602 | -9.293  |
| 5231832  | 73.608 | -9.174  |
| 524 232  | 73.613 | -9.105  |
| 5241032  | 73.616 | -9.052  |
| 5241832  | 73.619 | -9.004  |
| 525 232  | 73.623 | -8.954  |
| 5251032  | 73.630 | -8.901  |
| 5251832  | 73.639 | -8.850  |
| 526 232  | 73.647 | -8.812  |
| 5261032  | 73.651 | -8.787  |
| 5261832  | 73.646 | -8.762  |
| 527 232  | 73.640 | -8.751  |
| 5271032  | 73.632 | -8.756  |
| 5271832  | 73.625 | -8.760  |
| 528 232  | 73.620 | -8.777  |
| 5281032  | 73.616 | -8.817  |
| 5281832  | 73.616 | -8.870  |
| 529 232  | 73.619 | -8.922  |

| MMDDHHMM | LAT    | LON     |
|----------|--------|---------|
| 5291032  | 73.621 | -8.958  |
| 5291832  | 73.623 | -8.977  |
| 530 232  | 73.625 | -8.996  |
| 5301032  | 73.625 | -9.015  |
| 5301832  | 73.624 | -9.022  |
| 5311032  | 73.623 | -9.014  |
| 5311832  | 73.623 | -9.005  |
| 6 1 232  | 73.624 | -9.003  |
| 6 11032  | 73.623 | -9.024  |
| 6 11832  | 73.622 | -9.052  |
| 6 2 232  | 73.621 | -9.077  |
| 6 21032  | 73.622 | -9.077  |
| 6 21832  | 73.628 | -9.049  |
| 6 3 232  | 73.635 | -9.012  |
| 6 5 232  | 73.641 | -8.975  |
| 6 51032  | 73.623 | -9.102  |
| 6 51832  | 73.612 | -9.326  |
| 0 0 0    | 0.000  | 0.000   |
| 0 0 0    | 0.000  | 0.000   |
| 6 81032  | 73.621 | -9.338  |
| 6 81832  | 73.598 | -9.476  |
| 6 9 232  | 73.595 | -9.585  |
| 6 91032  | 73.594 | -9.591  |
| 6 91832  | 73.594 | -9.582  |
| 610 232  | 73.593 | -9.573  |
| 6101032  | 73.593 | -9.563  |
| 6101832  | 73.592 | -9.554  |
| 611 232  | 73.568 | -9.817  |
| 6111032  | 73.590 | -9.726  |
| 0 0 0    | 0.000  | 0.000   |
| 0 0 0    | 0.000  | 0.000   |
| 6251832  | 73.481 | -11.112 |
| 626 232  | 73.476 | -11.146 |
| 6261032  | 73.473 | -11.180 |
| 6261832  | 73.487 | -11.146 |
| 627 232  | 73.507 | -11.077 |
| 6271032  | 73.519 | -11.076 |
| 6271832  | 73.506 | -11.226 |
| 628 232  | 73.492 | -11.378 |

## INITIAL DISTRIBUTION LIST

|                                                                                                                           | No. Copies |
|---------------------------------------------------------------------------------------------------------------------------|------------|
| 1. Defense Technical Information Center<br>Cameron Station<br>Alexandria, VA 22304-6145                                   | 2          |
| 2. Library (Code 52)<br>Naval Postgraduate School<br>Monterey, CA 93943-5100                                              | 2          |
| 3. Chairman (Code OC/CO)<br>Department of Oceanography<br>Naval Postgraduate School<br>Monterey, CA 93943-5100            | 1          |
| 4. Library<br>Scripps Institution of Oceanography<br>University of California, San Diego<br>La Jolla, CA 92593            | 1          |
| 5. Robert H. Bourke (Code OC/BF)<br>Department of Oceanography<br>Naval Postgraduate School<br>Monterey, CA 93943-5100    | 2          |
| 6. Jean-Claude Gascard<br>Univ. Paris 6<br>LODYC Tour 14-2C<br>4 Place Jussieu F-75252<br>Paris Cedex 05 FRANCE           | 1          |
| 7. Newell Garfield III (Code OC/GF)<br>Department of Oceanography<br>Naval Postgraduate School<br>Monterey, CA 93943-5100 | 1          |
| 7. Dr. T. O. Manley<br>Department of Geology<br>Middlebury College<br>Middlebury, VT 05753                                | 1          |

9. LCDR D. H. McCarren 1  
USS THEODORE ROOSEVELT (CVN-71)  
FPO AE 09599-2871
10. Dr. Knut Aagaard 1  
NOAA/PMEL  
NOAA Bldg. #3  
7600 Sand Point Way N. E.  
Seattle, WA 98115
11. Institut fur Meereskunde der 1  
Universitat Hamburg  
Attn : Dr. Jens Meincke  
2000 Hamburg 54  
Federal Republic of Germany
12. Dr. E. Fahrbach 1  
Alfred Wegener Institute  
for Polar and Marine Research  
Am Handelshaven 12  
D-2850 Bremerhaven  
Federal Republic of Germany







DUDLEY KNOX LIBRARY  
NAVAL POSTGRADUATE SCHOOL  
MONTEREY CA 93943-5101

DUDLEY KNOX LIBRARY



3 2768 00308028 4